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ABSTRACT

To develop a coherent description of the knowledge and processes involved in skillful word recognition, a study was devised in which 16 adults participated in four related experiments. The purpose of the first experiment was to examine some basic aspects of the processing of words, pseudowords, and nonwords and to discover basic differences in processing that might underlie the word advantage (the relative perceptibility of words, compared to that of nonwords). The second experiment assessed the contribution of whole-word and letter cluster cues to the word advantage. The other two experiments focused on whether the word advantage can be wholly explained in terms of response bias or sophisticated guessing. The study yielded these results: the word advantage is mediated by perceptual processes; in terms of basic information processing, the processing of words and nonwords appears to be quite similar; and although identity and positional information are extracted by separate mechanisms, they exhibit a mutual dependence. The results are compatible with a criterion-bias model that attributes the word advantage to the relationship among single letters and lexical units in memory. (A bibliography and appropriate tables are appended.) (HAI)

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MODELS OF WORD RECOGNITION

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Abstract

Major hypotheses about the processes involved in word recognition are reviewed and then assessed through four experiments. The purpose of the first experiment was to examine some basic aspects of the processing of words, pseudowords, and nonwords, and beyond that, to discover basic differences in their processing that might underlie the word advantage. The second experiment was designed to assess the contribution of whole-word and letter cluster cues to the word advantage. Finally, Experiments III and IV were focused on the question of whether the word advantage can be wholly explained in terms of response bias or sophisticated guessing. Taken together, the results of these experiments were most compatible with criterion bias models. A version of the criterion bias model is suggested wherein the word advantage is attributed to interfacilitation among single letter and lexical units in memory.

Models of Word Recognition

The most fundamental, most studied, and yet most controversial issue in the field of reading is that of how written words are recognized. Although many plausible explanations have been proposed, each has its shortcomings. This paper begins with a review of the major classes of hypotheses about the word recognition process. Then four experiments are described which were intended to evaluate specific aspects of those hypotheses. Finally, the results are drawn together in an effort to develop a more complete model of the word recognition process.

Letter-based Hypotheses

The most common hypothesis about the recognition of words has been that it begins with the recognition of their component letters. Perhaps the strongest argument for this hypothesis is the very fact that our language is alphabetic. This property allows for great many words to be represented by ordered arrays of a few basic symbols. However, unless letters correspond to perceptual units, the resulting economy is only academic, not psychological, and it is not at all clear that the recognition of words does depend on the prior recognition of their component letters.

Experimental studies have shown that: short words can be read aloud as quickly as single letters (Cattell, 1885b, 1886a; Kolers, 1970; but see Gough, 1972); from single, brief exposures, people can typically report about four unrelated letters, but several words (Cattell, 1885a); at very brief exposure durations, recognition accuracy is poorer for single, isolated letters than for letters embedded in frequent words (Johnston & McClelland, 1974; Reicher, 1969; Wheeler, 1970); in target search tasks, words can be recognized faster than letters within words (Johnson, 1975; Sloboda, 1976); and finally, under

brief exposure conditions, people often claim to have "seen" a word completely and clearly, even when one or two of its letters has been omitted, substituted or mutilated (Pillsbury, 1897). Although some, if not all, of these effects are amenable to alternate interpretations, taken together they suggest that the recognition of a word does not depend on the prior encoding of its component letters--or at least not exclusively.

Whole Word Hypotheses

Effects like those described above are consistent with the hypothesis that whole words, rather than their component letters, correspond to the units of perception in reading. Much of the reading research conducted around the turn of the century was directed towards discovering the aspects of words' shapes that cue their identities (see Woodworth [1938] for a critical review), and such efforts seem to be returning to vogue (e.g. Haber & Haber, 1977; McClelland, 1977). Nevertheless it seems unlikely that word-shapes are the sole basis for word recognition, whether or not they contribute. We can recognize words in an innumerable variety of typestyles and scripts: does this mean that a given word has as many internal representations? Depending on the goodness-of-fit required for word recognition, the necessary number of internal models would approach infinity.

This problem of pattern recognition exists regardless of the unit of visual analysis. Just like words, single letters and literal features must retain their identities across an infinite number of variations in shape and size. The implication is that, whatever the unit of visual analysis, its interpretation must be conditional on its graphic environment. The advantage of the smaller units is, then, not that they would eliminate the pattern recognition problem, but that they would make it more tractable. Written

English consists of tens of thousands of words, 26 letters, and perhaps a few as five literal features. Therefore, for purposes of disambiguation, it must be far more informative per unit at the level of literal features or letters than at the level of words. Interestingly, this argument suggests its own hedge: the units of visual analysis and the units of perception need not be the same; while the former could correspond to the elements into which the input is initially parsed, the latter could correspond to the sets of those elements which must be considered conjointly to admit interpretation.

The strongest empirical objection to whole-word hypotheses is that they define a strict dichotomy between the ease of processing familiar words and unfamiliar graphemic strings. In contrast, it has been repeatedly demonstrated that nonwords that conform to the orthographic rules of English, or so-called pseudowords, can be recognized more quickly and accurately than strings of unrelated letters, all else being equal (e.g. Gibson, Pick, Osser & Hammond, 1962; Miller, Bruner & Postman, 1954; Mewhort, 1974). Moreover, there is some evidence that recognition is no easier for familiar words than for pseudowords (Baron & Thurstone, 1973; but see Manelis, 1974). While the relative ease of recognizing words and pseudowords suggests that the process uses information that is smaller than a word, the relative ease of recognizing pseudowords and random strings of letters suggests that the process uses information that is bigger than single letters.

Letter Cluster Hypotheses

Applying Occam's razor, one might hypothesize that the proper unit of perceptual analysis in word identification consists of groups of letters. Adopting this compromise, Gibson, Pick, Osser, and Hammond (1962) suggested that reading depends on the decoding of spelling patterns. A spelling

pattern was defined as any "letter group which has an invariant relationship with a phonemic pattern" (p. 30). In terms of explanatory power, the spelling pattern approach is superior to both the letter-by-letter and whole-word theories of reading as it simultaneously exploits the grapheme-to-phoneme correspondence of English and predicts that processing should become easier as orthographic regularity increases.

However, Smith and Spoehr (1974) have pointed out that the spelling pattern approach introduces a paradox of its own. That is, if word recognition depends on matching the appropriate parts of a visual input against internal spelling pattern units, there must be some means of first parsing the input into the proper units of comparison. If the units of perception were letters or words, then preliminary unitization could be based on the physical cue of interitem spaces, but no such trivial solution is apparent for spelling pattern units. No simple pattern matching routine will do since the spelling-to-sound correspondence depends not only on the position of the cluster within a string (e.g., GLURCK vs. CKURGL), but also rather extensively on the surrounding context (e.g., SIGNING vs. SIGNIFY or LEAD A HORSE vs. LEAD PIPE). Notably, the problem of parsing arises for any theory that posits a unit of analysis that is bigger than a letter but smaller than a word.

Simple Response Bias Hypotheses

An obvious alternative to perceptual explanations of the word advantage is the claim that it is produced entirely within the response system. When the effect is measured in terms of the speed of stimulus identification, the advantage of words over nonwords can be chalked off to response availability (Cattell 1885b, 1886b; Solomon & Howes, 1951). When the effect is reflected

by greater identification accuracy for words under tachistoscopic conditions, it is most simply attributed to response bias: since words are more frequent, they are guessed more often. However, Broadbent (1967) has shown that the a priori probability of guessing the correct word in such situations is far too small to account for the effect.

Complex Theories

In short, it seems that the word advantage can be simply attributed to neither stimulus perception nor response generation. Yet at least one of these types of explanations must be fundamentally correct: it must be the case either that words can get into the system more readily than nonwords, or that they can get out of the system more readily than nonwords, or both. The solution to this dilemma has been to posit that the word advantage arises at some interface between stimulus perception and response generation. These sorts of explanations can be divided into two classes: sophisticated guessing theories and criterion bias theories (Broadbent, 1967). Within both classes of theories, letters or their composite features are usually accepted as the units of visual analysis. Within both, the word advantage is attributed to the reader's familiarity or experience with the language. The critical difference between the two is that, according to sophisticated guessing theories, the reader's knowledge of the language is purposefully applied in the process of response generation, whereas according to criterion bias models, it passively exerts its effect during the course of perception.

Sophisticated Guessing Models. The basic idea underlying sophisticated guessing models is that when a graphemic string is presented for a brief duration, only a few letters or parts of letters are actually seen. When

subjects are forced to identify the stimulus, they must generate their best guess on the basis of this partial information. They then use the extracted visual information to delimit a set of possible responses and, finally, choose from among those candidates the one that best fits their linguistic intuitions. There are two basic versions of the sophisticated guessing model, corresponding to whether the candidate set consists of letters or words.

The first version of the model, in which the decision process applies to letter selection, has been elaborated by Wheeler (1970). According to this version, the word advantage arises when the subject has been able to extract enough visual information from the stimulus to have a fair idea of the identity of most of its letters. She or he then searches through the candidate sets for each letter with a bias towards outputting a combination that spells a word. As an example, suppose that a subject has extracted enough information from the stimulus to know that it has four letters and that the first is a B, a P or an R, the second is an O or a C, the third is an A, and the last is a T or an I. The only combination of candidates that yields a word is BOAT, and that will be the preferred response. By contrast, if the stimulus had been a nonword, the subject would have had no basis for selecting among the candidate letters, and the probability of erring would have been geometrically increased. In any case, Estes (1975) and Thompson and Massaro (1973) have reported evidence that is lethally damaging to this version of the model.

In the second and more frequently advocated version of the sophisticated guessing model, the decision process applies to word selection (e.g., Solomon & Postman, 1952; Newbigging, 1961; Savin, 1963; Broadbent, 1967; Catlin, 1969). This version has been most formally and completely stated by Rumelhart

and Siple (1974). In their formulation of the model, visual analysis focuses on components or fragments of literal features while the features themselves constitute the units of perception. Regardless of the orthographic goodness of a stimulus, the number and distribution of features that are perceived depends strictly on visual parameters such as the size (number of components) of the different features and the duration and signal-to-noise ratio of the display. Further, the set of response candidates is determined solely by the set of perceived features; any string is eligible provided a critical number of its features match those in the perceived set and none of them mismatches. If no string satisfies this criterion, then the subject's response can only be guided by her or his a priori expectations of what would be presented. Otherwise, the subject selects some response from the delimited set according to her or his estimates of both the a priori probability that the corresponding string would be presented and the probability that that string would yield the perceived set of features. Moreover, the a priori probability that the subject attaches to any given string presumably depends, first, on the degree to which she or he expects different classes of stimuli and, second, on the likelihood of the string within each of those classes. In Rumelhart and Siple's study, the stimulus classes were words, pseudowords, and nonwords, and the likelihoods of a string within each of the respective classes were taken to be subjective estimates of word frequency, positional bigram frequency, and the distribution of strings that would be obtained by randomly sampling letters from the alphabet, one by one, with replacement. Thus, according to Rumelhart and Siples' model, apparent differences in stimulus perceptibility actually reflect nothing more than a response bias which is jointly determined by the subject's understanding of the task and his or her linguistic intuitions.

This version of the sophisticated guessing model stands up to empirical tests quite well. For example, it correctly predicts that, given no bias to the contrary, high frequency words will be accurately identified more often than low frequency words (e.g., Howes & Solomon, 1951; Solomon & Postman, 1952; Broadbent, 1967), that pseudowords will be accurately identified more often than random strings of letters (e.g., Miller, Bruner, & Postman, 1954; Gibson, Pick, Osser, & Hammond, 1962; Baron & Thurston, 1973; Spoehr & Smith, 1975; McClelland, 1976), and that the differences in the report accuracy of pseudowords and low frequency words may be relatively small (Baron & Thurston, 1973). Further, it correctly predicts that errors in tachistoscopic accuracy tasks should tend to be visually similar to the actual stimulus (Newbigging, 1961). Finally, inasmuch as the response is determined by the subject's a priori expectations, it correctly predicts that response tendencies should be sensitive to experimental set (e.g., Aderman & Smith, 1971; Goldiamond & Hawkins, 1958; Haber, 1965) and contextual constraints (e.g., Tulving & Gold, 1963; Morton, 1969).

Criterion Bias Models. The complex theories that assert that the word advantage arises in the course of perception (e.g., Morton, 1969; Frederiksen, 1971; Smith, 1971; Treisman, 1971) are basically variants of Broadbent's (1967) criterion bias model. Broadbent's statement of the model was derived from signal detection theory. In essence, he assumes that associated with each item in the subject's response repertoire is a decision axis. In the absence of stimulation, the value of a given item on its decision axis can be described by a normal distribution with some neutral mean and spurious variance. The effect of the stimulus presentation is to increase the value of each item on its decision axis to the degree that it constitutes

a physical match with the stimulus information. An item becomes available as a potential response when it exceeds the threshold value on its decision axis. The word advantage derives from the assumption that the threshold value varies inversely with the frequency of the item. Thus, unlike the simple perceptual theories, the criterion bias model does not claim that the subject is more sensitive to higher frequency strings, but rather, that she or he is biased to accept a more probable stimulus on the basis of less sensory information.

As described, the criterion bias model sounds very similar to a sophisticated guessing model. In fact, under certain assumptions, they have been shown to make equivalent predictions (Nakatani, 1970). However, Broadbent stresses that the nature of the criterion bias is such that it must be a part of the perceptual system itself. Theorists who have attempted to explain the origins of such a perceptual bias have generally relied on the concept of redundancy (e.g., Wheeler, 1970; Smith, 1971; Manelis, 1974; McClelland, 1976). Smith (1971) has most completely elaborated the workings of such a system.

According to Smith's (1971) feature analytic model, the perception of both words and random letters is based on the extraction of literal features, and the difference in their perceptibility is due to the ways in which the featural information is analyzed. For the identification of individual letters, the extracted features are first fed through a bank of binary feature tests. The outcome of these tests is then compared to the feature vectors associated with each of the 26 letters to find the best fit. Word identification proceeds in exactly the same way except that the outcome of the feature tests for each letter is matched against the feature matrices associated with words. A given word matrix simply consists of the ordered set

of feature vectors corresponding to the ordered set of letters that spell the word.

The word advantage accrues from the sequential redundancy of English orthography. To illustrate, if the first letter of a word is identified as an H, the second letter can only be a vowel and the features necessary for its identification are only those that serve to distinguish among the vowels. Conversely, if the second letter is a particular vowel, there is a limited number of alternatives for the first letter. It can be seen that when such mutual dependencies exist among all of the letters of a string, as in a word, the amount of featural information required for its identification may be substantially reduced. By contrast, the absence of sequential redundancy in a random string of letters means that its accurate identification depends on a relatively complete encoding of each of its component letters. Thus, according to Smith's feature analytic model, the word advantage is not produced by biased guessing given partial information, but rather, as in Broadbent's (1967) criterion bias model, occurs because much less physical information is needed to determine the identity of a word than of a random string of letters.

The criterion bias model can also be adapted to fit many of the data on word recognition. For example, since the level of the criterion is supposed to vary inversely with item frequency (Broadbent, 1967; Morton, 1969), high frequency words are expected to be more perceptible than low frequency words. Further, since the quality that distinguishes pseudowords from random strings of letters is precisely orthographic redundancy, pseudowords are expected to be more perceptible than random strings of letters. Broadbent (1967) and Morton (1969) further allow that the effect of context or other manipulations

of string probability are to prime an item or increase its resting value above the neutral mean, thus increasing its perceptibility. Finally, if in the criterion bias model, as in Rumelhart and Siple's (1974) sophisticated guessing model, perception is based on preliminary feature extraction, errors are likewise expected to be visually similar to the stimulus (Newbigging, 1961).

Summary

Although none of the above classes of hypotheses is wholly defensible, none is wholly refutable either. Does the recognition process work with single letters, whole words, or letter clusters? While there are sound arguments in support of each of these positions, it seems that none of them is, in itself, adequate to explain the full range of phenomena associated with word recognition. Almost certainly the correct explanation involves some combination of these possibilities. But what combination? How are the different kinds of knowledge represented and how are they interrelated? And in what manner do they influence the recognition process? The descriptive advantage of the sophisticated guessing and criterion bias models derives primarily from the fact that they do assume multiple levels of stimulus processing. Even so, few of the complex models provide explicit answers to these questions, and to the extent that they do, there is little agreement among them as to what the answers are.

At a generic level, both the criterion bias and the sophisticated guessing models seem capable of handling many of the phenomena related to word recognition. The problem with respect to their defense is that both are capable of handling the same phenomena. The reason that these two classes of theories are so difficult to distinguish empirically is of course that

redundancy and statistical predictability are the same thing. Thus, any variable that alters the redundancy and, by implication, the perceptibility of a stimulus according to criterion bias models, must also alter its predictability or a priori expectancy according to sophisticated guessing models.

However, the real theoretical issue is not whether one or the other of these models is exclusively correct. Something like sophisticated guessing must be a normal component of the perceptual process. That is, we are constantly and effortlessly interpreting situations in which the sensory information is not sufficient to yield the percept. In these cases, we simply fill in the blanks as seems most probable. As an example, the last word of the phrase, "A stitch in time saves...," comes quickly to mind despite its physical absence. The real theoretical issue, then, is whether or not there is a perceptual component to the word advantage, and if so, how it operates.

The objective of this study was to develop a more complete and coherent description of the knowledge and processes involved in skillful word recognition. The purpose of the first experiment was to establish a broad empirical base from which we could decide how to design the subsequent experiments and against which we could interpret their results. The major purpose of the second experiment was to examine the role of whole-word and letter cluster patterns in word recognition. Finally, Experiments III and IV were focussed on the question of whether the word advantage reflects perceptual facilitation or whether it can be adequately explained by sophisticated guessing theories.

EXPERIMENT I

The purpose of Experiment I was to identify some basic aspects of the processing of words, pseudowords, and orthographically irregular nonwords. To this end, forced full report accuracy for the three stimulus classes was compared across a range of effective exposure durations through a backward masking paradigm. The data were examined for evidence of: (a) differences in retention of the three types of stimuli; (b) differences in sensitivity to the visual information in the three types of stimuli; (c) the independence with which the component letters of each of the types of stimuli are processed; (d) whether the component letters of the stimuli were encoded in series or in parallel; and (e) the frequency of letter transpositions associated with the three stimulus types.

Method

Subjects. Sixteen paid adults served as subjects. All had normal or corrected-to-normal vision. Half of the subjects were assigned to Group I and half to Group II.

Apparatus and Material. The stimuli consisted of two lists of 216 quadrigrams. Within each list one third of the stimuli were words, one third were orthographically regular pseudowords, and one third were orthographically irregular nonwords. The words were selected from the highest frequency four letter types in Carroll, Davies, and Richman's (1971) sample of third graders' reading materials (median frequency = 458/840847). Each word also occurred at least 100 times per million according to the Thorndike-Lorge General Norm (1944). For the generation of both pseudowords and nonwords, letters were sampled according to their simple frequency of occurrence in English

(Underwood & Schulz, 1960). This was done to ensure that under subliminal presentation conditions, the proportion of correctly guessed letters would be similar across the three stimulus types. For each pseudoword, the initial letter was selected according to the probability of its being the first letter of a four letter word and each successive letter was selected so as to maximize the corresponding positional bigram frequency according to Mayzner and Tresselt's (1965) norm for four letter words. All pseudowords used were pronounceable, but none was homophonic with real English words. Examples are berm, fint, pome, and thew. For each nonword, the initial letter was selected according to its simple frequency of occurrence in English, and the rest were selected such that all positional bigram frequencies were less than one according to Mayzner and Tresselt's sample. None of the nonwords was obviously pronounceable. Examples are IEVG, TGAC, RSAI, and UTSL.

The two lists of stimuli were comparable in terms of word frequency ($t(71) = 0.078$) and orthographic regularity as measured by the summed positional bigram frequencies (for words, $t(71) = 0.468$; for pseudowords, $t(71) = 0.168$). Further, the orthographic goodness of the words and pseudowords was comparable within both List I ($t(71) = 0.538$) and List II ($t(71) = 0.827$); to the extent that there was a difference, the pseudowords held the advantage.

Each list of 216 quadrigrams was sorted into nine blocks of 24. Within each block, there were eight quadrigrams of each stimulus type; across blocks there were three stimuli of each type in each serial position. Otherwise, the stimuli were ordered randomly within lists. Subjects in Group I received one list of stimuli, while those in Group II received the other. For half the subjects in each group, the order of the trial blocks was different and the order of the stimuli within blocks was reversed.

INSERT FIGURE 1

The stimuli were constructed from black, lower case, transfer letters (Letraset Clarendon Medium, 42 pt.) mounted on white index cards. Examples are given in Figure 1. The quadrigrams subtended a maximum area of 1.25° vertical by 2.25° horizontal of visual angle in the center of the visual field. Three pattern masks were constructed by positioning fragments of the characters within an area measuring 2.25° vertical by 3.25° horizontal of visual angle. The fixation point consisted of a white dot centered on a matte black field. The trials were presented via an Iconix Four-Field Tachistoscope at approximate luminances of 1.34 log foot lamberts for the stimulus and mask fields and 0.03 for the fixation field.

Procedure. On each trial, the subject said, "Ready," when she or he had fixated the fixation point. Then the experimenter pushed the start button which resulted in (1) an additional 500 msec of the fixation field, (2) a 5 msec presentation of the stimulus, (3) a blank interval, (4) a 50 msec presentation of the mask, and (5) a return to the fixation field at which point the subject was to respond. The duration of the interval between stimulus offset and mask onset was set at 0 msec for the first trial of each block and increased by 3 msec on each successive trial of the block. Thus, the effective exposure duration, as defined by the stimulus onset asynchrony (SOA), ranged from 5 msec on the first trial of each block to 74 msec on the 24th. The mask was changed after each block of trials.

Subjects were instructed to write down all four letters of each stimulus in the correct order on the answer sheet. They were instructed to guess if necessary, with the stipulation that blanks, X's, or any other constant and

arbitrary default responses were not acceptable. Each subject was given a series of 24 practice trials, followed by the nine experimental trial blocks. A session lasted about 30 minutes.

Results and Discussion

The data were first scored in terms of the number of correctly reported letters regardless of position. In an effort to correct for individual differences in visual sensitivity, subjects were matched at what was hoped to be a subjectively equal exposure duration. For each subject this duration was taken to be the briefest stimulus onset asynchrony (SOA) at which she or he correctly reported all four letters of any stimulus of any type. The accuracy curves that resulted are shown in Figure 2. The zero point on the abscissa denotes the first trial of a fully correct report for each subject. Shorter SOA's are denoted by negative numbers on the abscissa, and longer ones by positive numbers. Because of individual differences in the trial of first fully correct report, the points below -9 msec and above +45 msec of relative SOA represent data from a decreasing number of subjects.

INSERT FIGURE 2

The first surprise was that the SOA of the subjects' first fully correct report looks like a threshold. Prior to this trial there was little evidence of improvement in response accuracy and the functions for the three stimulus types were substantially overlapping. A split-half comparison of the numbers of letters correctly reported at the shorter versus longer negative relative SOA's revealed slight but significant increase in accuracy with time ($W(15)=9.5$, $p<0.05$, Wilcoxon test, Bradley, 1968). However, this effect disappeared when the data from -3 msec of relative SOA were excluded

($W(14)=34$, $p>0.05$). Friedman tests (Bradley, 1968, p.138) confirmed that neither the effect of stimulus type ($\chi^2(2)=2.38$, $p>0.05$) nor its interaction with SOA ($\chi^2(2)=2.84$, $p>0.05$) approached significance within this range. The stimulus functions were not even differentiable at -3 msec relative SOA ($\chi^2(2)=0.719$, $p>0.05$).

By contrast, after the trial of the first fully correct report, accuracy increased rapidly and the stimulus curves were clearly differentiated. The accuracy data for the proportion of the suprathreshold curves that represented all subjects (relative SOA's of 0 msec through 45 msec) were examined through an analysis of variance for a 16 X 16 X 3 (Subjects X Relative SOA X Stimulus Type) repeated measures design (Winer, 1971). This test yielded highly significant main effects of both stimulus type ($F(2,30)=79.23$, $p<0.001$) and relative SOA ($F(15,225)=74.89$, $p<0.001$) and a significant interaction ($F(30,450)=15.05$, $p<0.001$). A Newman-Keuls test verified that report accuracy was significantly greater for words than for pseudowords and nonwords, and for pseudowords than for nonwords ($p<.01$). The interaction reflects the fact that the stimulus effect was most marked at shorter suprathreshold SOA's; at the longest SOA's, accuracy was nearly perfect for all stimulus conditions.

Forgetting. The use of a full report procedure carries with it the concern that differences in performance may be due to differences in the memorability rather than the encoding of the stimuli. However, the extent to which this concern is real can be assessed from the relation between the stimulus effect and exposure duration. The rationale is that, all else being equal, the ease of retaining information, once encoded, should depend strictly on the nature of that information. Further, since whole words should be especially easy to retain while whole nonwords should be especially difficult,

differences between the memory loads associated with the three types of stimuli should be greatest at asymptote. Thus, to the extent that the stimulus effect is due to differential forgetting, it should be most pronounced at longer exposure durations. Conversely, if the stimulus effect is most marked at shorter exposure durations, then it cannot be primarily due to forgetting. Even in this case, an upper bound on the contribution of forgetting to the effect can be estimated from differences in report accuracy at asymptote.

Since the stimulus effect in this experiment was most pronounced at shorter suprathreshold SOA's, its primary determinant could not have been differential forgetting. Moreover, the convergence of the three curves at asymptote suggests that differential forgetting contributed minimally, if at all, to the stimulus effect.

Sensitivity Hypothesis. If subjects are differentially sensitive to the visual features of words, pseudowords, and nonwords, then their recognition thresholds should vary accordingly. As described above, report accuracy did not differ between stimulus types at negative relative SOA's. But, compared to -3 msec relative SOA, all three functions showed significant improvement at 0 msec relative SOA (Wilcoxon test: $W(15) = 0$ for words, $W(14)=2.5$ for pseudowords, and $W(13)=7.5$ for nonwords, $p<.01$). Thus, contrary to the sensitivity hypothesis, the trial of first fully correct report seems to correspond to a report threshold for all three stimulus types.

Independence of Letter Processing. If the component letters of a string were equally perceptible and processed independently, then, at any given SOA, the probability of correctly reporting an entire quadrigram should be equal to that of correctly reporting four letters. That is,

[1] $P_t(\text{Quadrigram}) = P_t(\text{Letter})^4$

where t refers to the particular SOA. These two probabilities were compared through a 16 X 16 X 3 X 2 (Subject X Relative SOA's X Stimulus Type X P_t(Quadrigram) vs. $P_t(\text{Letter})^4$) analysis of variance. It was found that P_t(Quadrigram) and $P_t(\text{Letter})^4$ differed significantly ($F(1,15) = 58.64$, $p<0.001$) but that the nature of the difference interacted with stimulus type ($F(2,30)=18.57$, $p<0.001$).

INSERT FIGURE 3

P_t(Quadrigram) and $P_t(\text{Letter})^4$ are shown in Figure 3 for each stimulus type. Whereas $P_t(\text{Letter})^4$ was significantly greater than P_t(Quadrigram) for nonwords ($t(15) = -3.35$, $p<0.01$) and pseudowords ($t(15)=-5.26$, $p<.01$), the opposite was true for words ($t(15)=2.92$, $p<.05$). The superiority of $P(\text{Letter})^4$ for nonwords and pseudowords suggests that the component letters of these strings were not equally perceptible. In fact, a 16 X 3 X 4 (Subjects X Stimulus Type X Serial Positions) analysis demonstrated that, in addition to the stimulus effect ($F(2,30) = 15.75$, $p<.001$), there was a marked serial position effect ($F(3,45) = 15.75$, $p<.001$). More specifically, the probability of correctly reporting a letter was inversely related to its serial position in the quadrigram. An interaction between string position and stimulus type ($F(6,90)=5.89$, $p<.001$) indicated that this relationship was significantly stronger for nonwords and pseudowords than for words. The fact that for words P(Quadrigram) exceeded $P(\text{Letter})^4$ <u>despite</u> this serial position effect, stands as strong evidence that their component letters are not processed independently. This nonindependence must be a major source of the word advantage; the question is how it is mediated.

Serial vs. Parallel Encoding. Several researchers have interpreted serial position effects like the one found here as evidence that the component letters of graphemic strings are encoded serially, from left-to-right (e.g., Gough, 1972; Spoehr & Smith, 1973). However, such serial position effects can also be accomodated by theories that assume parallel letter processing (e.g. Rumelhart, 1970). The importance of this issue lies in the way the two different modes of processing would constrain the kinds of interfacilitation that might occur between letters.

Given certain conditions, these two positions can be assessed from the way in which accuracy increases with effective exposure duration. Specifically, if letter encoding proceeds serially, then accuracy should increase linearly with SOA providing that the component letters of a string are encoded independently and that the mean encoding time per letter is independent of its serial position. Although the words in this experiment clearly violate the first condition, the nonwords and pseudowords do not. Moreover, the even decline in the serial position function for nonwords and pseudowords suggests that they meet the second condition as well; the proportion of correct responses was .88, .855, .83, and .80 for serial positions 1 through 4, respectively.

In view of this, the nonword and pseudoword functions between threshold and accuracy were evaluated for linearity. Curve-fitting procedures were not used because of the difficulty of defining an appropriate and unfudgeable comparison function. Instead, we compared the increase in SOA that each subject took to get at least half way from his or her subthreshold accuracy level to 100% accuracy with the increase in SOA that she or he took to get the rest of the way. To illustrate, subjects were shown three quadrigrams of each

type of each SOA, so, if a subject correctly reported 3 or 4 letters from pseudowords at -3 msec of relative SOA, then the increase in SOA until she or he first reported at least 8 letters correctly was compared with the increase in SOA from that point until she or he first reported all 12 letters correctly. If response accuracy increased linearly with exposure duration, then these values should have been equal. In fact, subjects took about twice as long to reach 100% from "half" accuracy (21.2 msec for nonwords and 15.6 msec for pseudowords) as they did to reach "half" accuracy from threshold (10.6 msec for nonwords and 7 msec for pseudowords); for both nonwords ($t(15) = 3.32$, $p<0.01$) and pseudowords ($t(15) = 3.34$, $p<0.01$) the difference was significant.

In short, accuracy did not increase linearly with SOA, and, by implication, the component letters of the stimuli were not encoded serially. Instead, the increase in accuracy was negatively accelerated across SOA's, which is consistent with parallel processing models.

Positional Accuracy. Rescoring the data such that a letter was only counted correct if it had been reported in the correct position, produced a marked change in the subthreshold accuracy functions (see Figure 4). Specifically, when report position was taken into account, accuracy was no longer constant, but increased significantly across this range (Wilcoxon test: $W(16)=9$, $p<.01$). This trend was still significant when the data from -3 msec of relative SOA were excluded ($W(13)=8$, $p<.01$). That positional accuracy increased across subthreshold SOA's while letter accuracy did not, implies that the two are mediated by separate mechanisms, as has been suggested by Finkel (1973) and Estes (1975). Moreover, this improvement implies that report accuracy rose above chance during this interval. Since the number of

correctly reported letters regardless of position was relatively constant across the subthreshold interval, it must have been above chance virtually throughout. This means that 0 msec of relative SOA should be interpreted as the recognition threshold for quadrigrams rather than as a visual recognition threshold *per se*. Apparently, the quadrigram recognition threshold depends on a critical increase not in the amount of letter information that is extracted, but in the amount of positional information that is extracted.

INSERT FIGURE 4

At suprathreshold SOA's, the stimulus effect became much more pronounced when positional accuracy was taken into account. A Subject X Relative SOA X Stimulus Type X Correct Letters vs. Correct Letters in Position (16 X 16 X 3 X 2) analysis of variance reaffirmed the significance of relative SOA ($F(15,225) = 79.15$, $p<.001$), stimulus type ($F(2,30) = 123.10$, $p<.001$), and their interaction ($F(30,450) = 5.28$, $p<.001$), and in addition, revealed significant effects of positional scoring ($F(1,15) = 59.53$, $p<.001$) and its interaction with relative SOA ($F(15,225) = 11.77$, $p<.001$) stimulus type ($F(2,30) = 68.63$, $p<.001$) and both ($F(30,450) = 2.02$, $p<.001$).

To identify the source of the interaction between positional accuracy and stimulus type, the difference between the number of correctly reported letters with and without positional considerations was assessed through a 16 X 3 (Subjects X Stimulus Type) analysis of variance. A Newman-Keuls test indicated that the significant effect of stimulus type ($F(2,45) = 39.92$, $p<.001$) was almost entirely attributable to the nonword condition. Whereas positional accuracy did not significantly differ between words and pseudowords, it was, in either case, significantly greater than for nonwords ($p<.001$).

There are several possible explanations of why the letters of words and pseudowords should end up in the correct order more often than those of nonwords. First, it is conceivable that the perception of letters is unordered, and that the subjects order their reports according to their knowledge of English orthography. However, if this explanation were complete, then a fair number of pseudowords should have been incorrectly permuted, since most of them were anagrams of real words; in contrast, among the completely reported pseudowords, all but three were ordered correctly.

A second possibility is that letter position is generally perceived, but that it is forgotten more easily when not reinforced by orthographic constraints. However, if this explanation were complete, then the probability of losing positional information should have been invariant with SOA; in contrast, it was increasing.

A third possibility is that the position of a letter is only encoded relative to the positions of the other letters in the string. In this case, positional accuracy should depend on the completeness of stimulus recognition, and, therefore, would be expected to increase with exposure duration and to vary across stimulus types. Yet, this explanation cannot be complete either, since even among fully reported stimuli, nonwords were far more likely to be misordered (69 out of 489) than were words (1 out of 806) or pseudowords (3 out of 611). The explanation might be salvaged by assuming that the order of the nonword letters was especially forgettable, except that this assumption, in turn, implies that the tendency to permute the letters of fully reported nonwords should not vary with SOA; in contrast, fully reported nonwords were significantly more likely to be ordered correctly at longer than at shorter suprathreshold SOA's ($t(15)=4.27$, $p<0.01$).

Apparently transposition errors cannot be wholly attributed to either constructive processes or forgetting. Rather, the stubborn covariance of positional accuracy with exposure duration indicates that part of the difficulty is due to perceptual limitations: evidently the extraction of positional information is a fairly time-consuming process.

Estes (1975) and McClelland (1976) have also noted a differential tendency toward letter transpositions among nonwords. To explain the phenomenon, Estes suggested that "appreciable uncertainty attaches to the information concerning location of a character...that is entered into short-term memory (p. 137)," and that, in judging the relative positions of characters, individuals supplement the "fallible positional information" with their knowledge of orthographic redundancy. These data support Estes' explanation, but further, suggest a reason for the positional uncertainty. Both the subthreshold and suprathreshold data indicate that the identity and position of a character in an orthographic sequence do not correspond to integral perceptual dimensions and that positional information takes especially long to encode.

Summary of Experiment I

The accuracy functions for words, nonwords, and pseudowords were found to be discontinuous at the SOA of the first fully correct report. Across shorter SOA's, letter report accuracy was relatively poor and constant and did not differ between stimulus types. Across longer SOA's, report accuracy increased rapidly and became strongly associated with stimulus type: words were reported most accurately, followed by pseudowords, and then nonwords. The SOA of the first fully correct report was therefore interpreted as a recognition threshold for quadrigrams.

The differences in report accuracy for words, pseudowords, and nonwords at suprathreshold SOA's could be ascribed to differences in neither sensitivity nor forgetting. However, there was a marked nonindependence among the component letters of words that was not apparent among the component letters of nonwords or pseudowords. In addition, the probability of subjects' reporting a letter in its correct position was found to depend on both stimulus type and exposure duration. It was argued that positional information is processed by a separate mechanism from item information, and that the recognition threshold for quadrigrams depends on the extraction of a critical amount of order information.

EXPERIMENT II

While it is clear that word-shape cues are not the sole basis for word recognition (Woodworth, 1938), it is not clear whether they contribute. Because of this ambiguity, most experimenters have used uppercase stimuli so as to minimize differences in word shape. To the contrary, the lower case letters used in Experiment I of the present study would seem to provide ideal conditions for the exploitation of whole-word cues. Indeed, the nonindependence observed among the letters of words in Experiment I implies that, in some sense, the whole word is greater than the sum of its parts. Experiment II examined the extent to which this nonindependence is attributable to the visual patterns of words.

There is considerable evidence that distortions of a word's shape are detrimental to its perception. For example, words can be processed more rapidly when they are printed in lower case type than when they are printed in

all capitals (Woodworth, 1938). Processing is even slower if letter case is alternated within a word (Coltheart & Freeman, 1974). If the size of the letters varies within a word, processing is still slower, regardless of case variations (Smith, Lott, & Cronell, 1969). Yet, none of these studies reveals whether variations in typeface affect the discriminability of words above and beyond the discriminability of their component letters.

Recently McClelland (1976) has obtained evidence pertaining to this issue. He compared threshold recognition accuracy for words, pseudowords, and nonwords, printed in lower case, upper case, or mixed (upper and lower) case fonts. He argued that if word perception depends on preliminary letter identification, as opposed to word-shape cues, then the word advantage should persist even in the mixed case condition. In fact, he obtained a significant word advantage by every measure, regardless of case manipulations.

However, when McClelland's question is turned around to ask whether the shapes of words or frequent letter clusters contribute to the word advantage, the answer is less clear. That is, if the perception of words, pseudowords, and nonwords were similarly dependent on single letter identification, then changes in letter discriminability should have had comparable effects on the recognizeability of all three. By contrast, McClelland found that mixed case stimuli reliably resulted in a decrement in recognition accuracy for words and pseudowords, but not for nonwords. His data thus leave open the possibility that the primary effect of case manipulations was to decrease the value of some class of cues which were effective only for words and pseudowords in the first place -- the visual patterns of words or frequent letter clusters are obvious candidates.

In Experiment II, the subjects and procedure were the same as in Experiment I except that the stimuli were constructed from a variety of fonts. The fonts were chosen to be as diverse as possible, with the intention of maximizing the necessity of letter-by-letter processing. If the stimulus effect in Experiment I were partially mediated by the shapes of words or frequent letter clusters, then it should be reduced in Experiment II. Further, this reduction should be attributable to a decrement in report accuracy for words, and possibly pseudowords, relative to nonwords.

Method

Subjects. The 16 subjects were the same as in Experiment I. The Group that had been tested on the first stimulus list in Experiment I, received the second list in Experiment II, and vice versa.

Apparatus and Material. The apparatus and materials for Experiment I and II were identical except with respect to stimulus construction. For Experiment II, the fonts varied in size, case, and style. The fonts from which uppercase letters were selected included: Alternate Gothic No.2 (Letraset 48 pt.); Arnold Bocklin (Letraset 42 pt.); Blanchard Solid (Letraset 42 pt.); Caslon 540 Italic (Chartpak 36 pt.); Century Schoolbook Bold (letraset 30 pt.); Davida Bold (Chartpak 36 pt.); Desdemona Solid (Letraset 48 pt.); Herkules (Letraset 48 pt.); Lydian Cursive (Transartype 36 pt.); Microgramma Medium Extended (Letraset 36 pt.); Mistral (Letraset 48 pt.); Studio (Transartype 36 pt.); and Zipper (Letraset 42 pt.). The fonts from which the lowercase letters were selected included: Arnold Bocklin (Letraset 42 pt.); Blanchard Solid (Letraset 42 pt.); Caslon 540 Italic (Letraset 48 pt.); Clarendon Medium (Letraset 42 pt.); Futura Medium

(Letraset 60 pt.); Hauser (Transartype 48 pt.); Old English (Chartpak 48 pt.); Playbill (Letraset 60 pt.); Smoke (Chartpak 48 pt.); Studio (Transartype 36 pt.); and Zipper (letraset 42 pt.). Three people looked through the letters both before and after stimulus construction; any character that was judged to be ambiguous or particularly confusable by any of these three people was excluded from the stimulus set. Script allographs, like *s*, *f*, and *r*, were also excluded. During stimulus construction, the characters were sampled randomly with the restriction that each character and typeface be represented with approximately equal frequency across stimulus types and lists. Examples of the stimuli are shown in Figure 5.

INSERT FIGURE 5

Procedure. The procedure was the same as in Experiment I, except that subjects were informed of and practiced with typographically irregular stimuli.

Results and Discussion

Overall Results. As in Experiment I, the data were first scored in terms of the number of correctly reported letters regardless of position, and subjects were matched at the trial of their first, fully correct report. The resulting accuracy curves are plotted as a function of relative SOA in Figure 6. Because of individual differences in the threshold asynchrony, the points below -9 msec and above +45 msec represent data from a decreasing number of subjects.

INSERT FIGURE 6

As in Experiment I, the three functions appear to be relatively constant and overlapping across the subthreshold interval. A Wilcoxon test confirmed that report accuracy did not significantly increase at longer subthreshold durations ($W(14) = 24$, $P > .05$). According to Friedman tests, the differences between stimulus types ($\chi^2(2) = 3.88$, $p > .05$ and their interaction with SOA's ($\chi^2(2) = 1.16$, $p < .05$) were also nonsignificant within this range. Thus, the trial of first fully correct report seems to be a good index of the quadrigram recognition threshold for Experiment II as well.

The portions of the suprathreshold functions that represented all subjects (relative SOA's of 0 to 45 msec) were compared through a 16 X 16 X 3 (Subjects X Relative SOA X Stimulus Type) repeated measures analysis of variance. The differences between stimulus type ($F(2,30) = 85.21$, $p < .001$), the increase in accuracy with SOA ($F(15,225) = 46.36$, $p < .001$), and their interaction ($F(30,450) = 1.85$, $p < .01$) were again significant.

An intriguing aspect of this experiment was that most subjects remarked that they could not see the typographic irregularities except at relatively long SOA's. At shorter SOA's, they reported an illusion that the quadrigrams appeared to be printed in regular, block type. The failure of subjects to notice whether stimuli were printed in upper, lower, or mixed case type has been reported by several previous investigators (Coltheart & Freeman, 1974; McClelland, 1976; Pillsbury, 1897). However, in each of those studies, case manipulations were either unpredictable or totally unexpected. In the present study, subjects knew that none of the stimuli were typographically regular. Yet, they still insisted that the stimuli "looked" regular at shorter SOA's. This phenomenon seems more compatible with the view that letter recognition proceeds by matching visual information against prototypical letter models in

memory (Gibson, 1965; Posner, 1969), than with the view that visual information is shuttled through sets of specific feature detectors to obtain an amorphous identity (Smith, 1971).

Accuracy: Experiment I vs. Experiment II. The probability of correctly reporting letters during the subthreshold interval was significantly greater for Experiment I than Experiment II ($t(15) = 2.35$, $p<.05$ although the actual difference was only 4.2%. In addition, there was a slight but significant increase in the threshold asynchrony from Experiment I to Experiment II ($W(9) = 4$, $p<.05$). Both of these effects may have been due to the decreased discriminability of the letters in Experiment II.

The suprathreshold report functions between 0 and 45 msec of relative SOA were compared across experiments through a 16 X 16 X 3 X 2 (Subjects X Relative SOA X Stimulus Type X Experiments) analysis. The effects of relative SOA ($F(15,225) = 94.77$, $p<.001$), stimulus type ($F(2,30) = 98.99$, $p<.001$), and their interaction ($F(30,450) = 4.97$, $p<.001$) were of course highly significant. The effect of experiments was also very significant ($F(1,15) = 66.85$, $p<.001$), as report accuracy was generally lower in Experiment II than in Experiment I. Because of the ceiling effect at longer SOA's, there was also an interaction between experiments and relative SOA ($F(15,225) = 2.05$, $p<.05$). But, most importantly, the effect of experiments did not significantly interact with stimulus type ($F(2,30) = 3.19$, $p>.05$). Moreover, it is difficult to argue that there really was an interaction but that it was concealed by ceiling effects since the interaction of experiments, stimulus type and relative SOA was also nonsignificant ($F(30,450) = 1.14$, $p>.05$).

The same pattern of results was obtained when the proportions of fully reported quadrigrams were compared across experiments. There were highly

significant main effects of stimulus type ($F(2,30) = 167.15$, $p < 0.001$), relative SOA ($F(15,225) = 64.70$, $p < 0.001$), and experiments ($F(1,15) = 103.83$, $p < 0.001$), and significant interactions between relative SOAs and both stimulus type ($F(30,450) = 3.06$, $p < 0.001$) and experiments ($F(15,225) = 4.49$, $p < 0.001$). But again, neither the stimulus type X experiment interaction ($F(2,30) = 2.71$, $p > 0.05$) nor the triple interaction ($F(30,450) = 1.03$, $p > 0.05$) was significant.

The question remains as to why these data are discrepant with McClelland's (1976). On close examination, the answer seems to be that they are not. Each subject in McClelland's study was tested at a single exposure duration, adjusted such that, across all stimuli, his or her report accuracy would average between 40% and 60% correct. Judging from McClelland's accuracy data, his subjects' exposure durations corresponded to relative SOA's between +3 and +6 msec in this study. If we compare our own subjects' performance on regular and irregular typographies within this exposure interval, we find, just as McClelland did, that the irregular typography resulted in significantly poorer performance on words ($t(15)=2.96$, $p<0.01$) and pseudowords ($t(15)=4.48$, $p<0.01$) but not nonwords ($t(15)=0.84$, $p>0.10$). However, in the context of the range of exposure durations used in this experiment, the interpretation that the irregular fonts affected words and pseudowords differently from nonwords seems unwarranted. Rather, the more plausible explanation of these uneven effects is that at such brief exposure durations, guessing contributes so heavily to the nonword performance that it camouflages the effect of fonts.

The implication of these analyses is that the shapes of words and letter clusters contribute minimally to the word advantage. If the typographic

irregularities had altered the cue value of word shapes, then they should have been most damaging to the recognition of words. Similarly, if they had altered the cue value of frequent bigram patterns, then they should have been more damaging to words and pseudowords than to nonwords. That the typographic irregularities produced comparable decrements for all three stimulus types, strongly suggests that their effect was almost wholly located at the level of single letter discriminability. This, in turn, implies that the recognition of graphemic strings, regardless of their orthographic goodness, is mediated by single letter identification.

Forgetting. Since the performance of many subjects did not reach asymptote within Experiment II, the contribution of differential forgetting to the stimulus effect is difficult to estimate. However, since the differences between stimulus types did diminish significantly with increasing SOA, forgetting cannot be cited as the sole source of the stimulus effect. Moreover, if memory load is primarily determined by the nature of the encoded stimulus, then there is no reason to expect that differences in retention should be more pronounced in Experiment II than in Experiment I.

Sensitivity Hypothesis. Experiment II also provided little support for the sensitivity hypothesis. As previously described, the accuracy of letter recognition did not significantly differ between stimulus types at subthreshold SOA's. But at 0 msec of relative SOA, each of the three stimulus functions was clearly above its subthreshold level (Wilcoxon test: $W(15) = 2$ for words; $W(13) = 6$ for pseudowords; and $W(16) = 21$ for nonwords, $p<.05$). The failure of the sensitivity hypothesis is consistent with the evidence that stimulus perception was based on preliminary letter identification.

Independence of Letter Processing. As in Experiment I, the independence of letter processing was assessed by comparing the probability of correctly reporting a whole string, P(Quadrigram), with the probability of correctly reporting four independent, equally perceptible letters, $P(Letter)^4$, through a 16 X 16 X 3 X 2 (Subjects X Relative SOA X Stimulus Type X P(Quadrigram) vs. $P(Letter)^4$) analysis. The difference between P(Quadrigram) and $P(Letter)^4$ was again significant, as were its interactions with stimulus type ($F(2,30) = 43.86$, $p<.001$) and relative SOA ($F(15,225) = 1.88$, $p<.05$). The interaction with stimulus type is again the combined product of a general serial position effect and a particular nonindependence among the letters of words. Whereas $P(Letter)^4$ exceeded P(Quadrigram) for both pseudowords ($t(15) = -5.99$, $p<.01$) and nonwords ($t(15) = -5.99$, $P<.01$), the opposite was true for words ($t(15) = 3.08$, $p<.01$). Because accuracy did not decrease linearly across serial positions for pseudowords and nonwords (79%, 78%, 73%, 66% for positions 1 through 4), none of the data were evaluated for serial versus parallel encoding.

Positional Accuracy. As in Experiment I, when position was taken into account, a reliable increase in accuracy appeared across the subthreshold SOA's (Wilcoxon test: $W(12) = 0$, $p<.01$). This is, again, to be contrasted with the relative constancy of the subthreshold functions when responses were scored regardless of position.

The suprathreshold functions for correctly reported letters with and without positional considerations were compared through a 16 X 16 X 3 X 2 (Subjects X Relative SOA X Stimulus Type X Correct Letters vs. Correct Letters in Position) analysis of variance. In addition to the usually significant ($p<.001$) effects of relative SOA, stimulus type, and their interaction, the

effect of positional scoring ($F(1,15) = 188.44$, $p<.001$) and its interactions with relative SOA ($F(15,225) = 6.92$, $p<.001$) and stimulus type ($F(2,30) = 95.11$, $p<.001$) were all highly significant.

For each stimulus type, the difference in accuracy with and without positional considerations was evaluated through a 16 X 3 (Subjects X Stimulus Type) analysis of variance. A Newman-Keuls test indicated that the significant effect of stimulus type ($F(2,30) = 102.21$, $p<.001$) was again almost entirely attributable to the nonword condition. Whereas positional accuracy did not significantly differ between words and pseudowords, it was for either of these conditions, significantly greater than for nonwords ($p<.01$).

The interaction between positional accuracy and relative SOA again indicated that positional accuracy increased with effective exposure duration. Because the number of fully reported nonwords was so small, no analysis of temporal trends in their permutation was feasible. However, across all subjects, the proportion of fully reported nonwords that were not permuted shifted from 0.63 at shorter suprathreshold SOA's to 0.83 at longer suprathreshold SOA's. Thus, as in Experiment I, the suggestion is that item and positional information are not entirely integral, and that of the two, positional information takes longer to encode.

Summary of Experiment II

The typographic irregularities introduced in Experiment II produced a marked reduction in report accuracy. However, this decrement did not significantly differ between stimulus types. Thus, these data do not support the hypothesis that the word advantage is partially mediated by visual cues

corresponding to the shapes of words or frequent letter clusters. Instead, the data converge on the hypothesis that the recognition of words, pseudowords, and nonwords, alike, depends upon preliminary letter identification. Introspective reports further suggest that letter identification proceeds by matching visual information against memory models of prototypical letters. In most other respects, the results of Experiment II qualitatively replicated those of Experiment I.

EXPERIMENT III

The results of Experiments I and II resolve many of the issues surrounding the word advantage. However, the question of whether or not there exists a perceptual component to the effect was left largely unanswered. On the basis of Experiments I and II, the most that can be said with respect to the perceptual facilitation of words, is that if it exists, it operates above the level of visual feature extraction. Experiment III was specifically designed to determine whether or not perceptual factors contribute to the word advantage. The stimuli were the same as in Experiment I, and recognition accuracy was again measured as a function of effective exposure duration. Experiment III primarily differed from Experiment I in that the subjects' task was not to report each stimulus, but simply to decide whether or not it was a word.

The premises underlying Experiment III were, first, that the perception of a graphemic string is based on preliminary letter identification, and, second, that the completeness of the percept increases gradually, if probabilistically, with effective exposure duration. It was further assumed that, on any given trial, if subjects have extracted some critical minimum of

information from the stimulus, they will know whether or not it was a word; otherwise, they will not.

The resulting perceptual situation may be summarized as:

[2]

Stimulus	State W	State $\overline{W}$	State ?
Word	w_t	0	$1-w_t$
Pseudoword	0	p_t	$1-p_t$
Nonword	0	n_t	$1-n_t$

where w_t, p_t, and n_t signify the probability that a word, a pseudoword, or an nonword, respectively, can be adequately perceived at an effective exposure duration of t. The states W, $\overline{W}$, and ? correspond to the subject's knowing that the stimulus was a word, was not a word, or just not knowing, respectively.

These perceptual states can be simply mapped into responses as follows. If a stimulus evokes state W, then the subject should respond that it was a word. Similarly, if a stimulus evokes state $\overline{W}$, the subject should respond that it was not a word. However, whenever a stimulus evokes the ? state, the subject must guess. Thus, the response matrix may be represented as:

[3]

State	Response W	Response $\overline{W}$
W	1	0
$\overline{W}$	0	1
?	g	1-g

where g denotes the bias towards guessing that the stimulus is a word given state ?. All together, then, the probability that a given stimulus will result in a word or not-word response is:

[4]

Stimulus	Response: W	Response: $\overline{W}$
Word	$w_t + g(1-w_t)$	$(1-g)(1-w_t)$
Pseudoword	$g(1-p_t)$	$p_t + (1-g)(1-p_t)$
Nonword	$g(1-n_t)$	$n_t + (1-g)(1-n_t)$

Each individual's response bias, g, can be directly taken from her or his subthreshold response distributions--where w_t, p_t, and n_t equal 0. Assuming that this bias is constant across SOA's, the values of w_t, p_t, and n_t, can then be estimated from her or his response distribution at each suprathreshold duration.

On first consideration, it might seem that if the stimulus types are equally perceptible, then the values of w_t, p_t, and n_t, should be equal. However, the problem is not that simple. If stimulus recognition is based on preliminary letter identification, then n_t should exceed both w_t and p_t. This is because the categorization of a nonword can be based on the perception of as few as two of its letters. By contrast, the categorization of both words and pseudowords depends on virtually complete encoding. Noteably, the value of p_t may underestimate the perceptibility of pseudowords to the extent that they are adequately perceived, but erroneously categorized as words. Although the value of p_t is uninterpretable, the inclusion of pseudowords in the design was purposeful. If pseudowords were not present, then the categorization of both words and nonwords could have been based on minimal processing. Inasmuch as pseudowords served as a foil for words, they insured that w_t would reflect the perceptibility of whole words.

In short, the critical comparison in this experiment is between the values of w_t and n_t. Under the null hypothesis, n_t should be equal to or

greater than w_t at intermediate exposure durations. If by contrast, w_t exceeds n_t, it would constitute strong support for the perceptual facilitation of words.

Method

Subjects. The subjects were eight, paid adults. All had normal or corrected-to-normal vision.

Apparatus and Material. The stimulus set consisted of 150 words, 75 pseudowords, and 75 nonwords. It included the 144 words from Experiment I, plus six new, high frequency words. The pseudowords and nonwords were randomly selected from those used in Experiment I. The apparatus and materials were otherwise the same as in Experiment I.

Procedure. Each subject received 600, forced-choice trials, equally apportioned across SOA's of 5, 15, 25, 35, and 45 msec. At each SOA, one half of the stimuli were words, one quarter were pseudowords, and one quarter were nonwords. The orders of the stimuli, the stimulus categories, and the SOA's were separately randomized across trials for each subject and experimental session.

The subject's task was to report on every trial whether or not the stimulus was a word. He was told that half of the stimuli were words and that half of them were not. He was also warned that some of the nonwords looked very much like words, but assured that all of the real words would be very familiar.

Each subject was run in two 1/2 hour sessions. Each of the 300 stimuli was presented once per session. At the beginning of each session, the subject was given 24 warm-up trials in descending order of SOA, as in Experiments I

and II. After every 25th trial, the mask was changed. In all other respects, the procedure was the same as in Experiment I.

Results and Discussion

The distribution of erroneous responses was analyzed across sessions (2) and stimulus conditions (3), and only the effect of stimulus condition ($F(2,14) = 4.83$, $p<0.05$) was significant. Since there was no significant difference between sessions in either the number or distribution of errors, the data from the two sessions were combined. For each subject, the percentage of correct responses is given as a function of SOA and stimulus type in Table 1.

INSERT TABLE 1

Inasmuch as response accuracy at 5 msec of SOA was very close to chance (49.8%), the response distribution at this SOA should provide a good estimate of the base response bias. According to the model proposed in the introduction to this experiment, performance at longer SOA's can only improve, as it can only change as the result of increases in the amount of perceived information. By contrast, for five of the eight subjects, performance on nonwords and pseudowords got worse at longer SOA's. As this finding can only mean that the bias factor, g, was not invariant with time, it immediately invalidates the proposed model. If the data are used to solve for the parameters in matrix [4], then, mathematically, we get negative perceptibility values; conceptually, we get nonsense. Since response accuracy did increase most rapidly for words, these data might still be interpreted as reflecting a perceptual advantage for words. However, there is an alternative model, based strictly on response strategies, that fits the data well.

Specifically, suppose that for each SOA, t, there corresponds a probability, σ_t, that something will be perceived and a probability $1-\sigma_t$ that nothing will be perceived, and that these probabilities do not vary with stimulus types. Suppose further, that whenever nothing is perceived, the subject simply guesses whether or not the stimulus was a word, but that whenever something is perceived, she or he pursues a strategy of looking for orthographic violations. If a violation is found, then the subject responds, "not a word"; otherwise, she or he responds "word". The effect of this strategy would be to shift the response bias from some base level towards words with increasing SOA.

In matrix form, this perceptual situation can be represented as:

[5]

Stimulus	State: X	State: O
S_i	σ_t	$1-\sigma_t$

where S_i is a string of type i ($i \in$ {word, pseudoword, nonword}), and the states, X and O, designate the perception of something or nothing, respectively.

Similarly, the response selection matrix can be represented as:

[6]

State	Response: W	Response: $\overline{W}$
X	$1-v_{i,t}$	$v_{i,t}$
O	g	$1-g$

where $v_{i,t}$, the probability of detecting an orthographic violation in a stimulus of type i at an SOA of t.

Since the probability of detecting an orthographic violation in a word, $v_{w,t}$, should equal 0, the response distribution at an SOA of t may be fully specified as:

[7]

Stimulus	Response: W	Response: $\overline{W}$
S_w	$\sigma_t + (1-\sigma_t)g$	$(1-\sigma_t)(1-g)$
S_p	$\sigma_t(1-v_{p,t}) + (1-\sigma_t)g$	$\sigma_t v_{p,t} + (1-\sigma_t)(1-g)$
S_n	$\sigma_t(1-v_{n,t}) + (1-\sigma_t)g$	$\sigma_t v_{n,t} + (1-\sigma_t)(1-g)$

The values of g, σ_t, $v_{p,t}$, and $v_{n,t}$ are given for each subject in Table 2. The value of g was obtained from the response distribution at 5 msec of SOA by setting σ_5 equal to zero. The value of g was then substituted into the equation between the theoretical and observed performance on words to obtain σ_t. Finally, $v_{p,t}$ and $v_{n,t}$ were obtained by substituting g and σ_t into the equations for pseudoword and nonword performance, respectively.

INSERT TABLE 2

The probabilities of both perceiving something (σ_t) and detecting orthographic violations in the percept ($v_{i,t}$) generally increase with SOA as would be expected. Further, the fact that $v_{n,t}$ generally exceeds $v_{p,t}$ is consonant with the orthographic differences between nonwords and pseudowords. Although the entries for several subjects at 15 msec of SOA are inordinate, these estimates are not very reliable since performance was so close to chance at this point. To this extent, then, the model seems quite plausible.

However, there are a couple of ways in which the model does not sit well. First, the values of g in Table 2 are puzzling. Since subjects were told that half of the stimuli were words, it is not clear why the base response bias

should have tended so strongly towards nonwords. It is tempting to believe that subjects heeded this warning, since over all trials they divided their responses more or less evenly between words (54%) and nonwords (46%). Second, subjects' introspective reports suggested a different explanation for the response distribution. When asked about their response strategies, they generally replied that the words "popped out" at them so that if a stimulus was unclear, they tended to guess that it was a nonword; if it seemed clear, they tended to guess that it was a word even if they missed it.

However plausible the response strategy model might seem, the possibility that words were in fact more perceptible than pseudowords or nonwords cannot be ruled out. That is, under the response strategy model, "word" responses are a default option: they will occur whenever something is at least partially perceived but no orthographic violations are detected. Since words must be orthographically acceptable, partially encoded words will always elicit correct responses. However, fully encoded words must also elicit correct responses. Thus, there is no way to determine how clearly words actually were perceived in this experiment.

Summary of Experiment III

The purpose of Experiment III was to determine whether perceptibility differs for words, pseudowords, and nonwords. To this end, subjects were given a forced-choice categorization task in which performance was measured as a function of SOA. Although performance was most accurate for words, the data were generally consistent with a model which assumed no differences in perceptibility across stimulus classes. According to this model, differential accuracy across stimulus conditions reflects a response strategy.

Specifically, the categorization of a partially encoded stimulus depends on whether or not any orthographic violations are detected. On the other hand, subjects' introspective reports suggested that words were, in fact, more perceptible than other stimuli. Given the possibility that word responses were resorted to as a default option under conditions of uncertainty, there was no way to verify their claim.

EXPERIMENT IV

Experiment IV was a second attempt to assess the relative perceptibility of words. As in Experiment III, the method involved a categorization task, except that this time guessing was discouraged. The rationale was that if the word category served as a default option, then its advantage should disappear if guessing were eliminated.

Specifically, the necessity of guessing was removed by giving subjects the option of saying, "I don't know". The utility of guessing was minimized through a pay-off matrix: for each correct response, the subject won one cent; for each incorrect response, she or he lost 5 cents; and for each noncommittal response, the subject neither won nor lost any money. According to decision theory (Coombs, Dawes, & Tversky, 1970), the acceptability of a gamble depends on both the stakes and the odds of winning. Since the stakes did not vary in this experiment, differences in the probability of gambling should depend strictly on the odds of winning, which, in turn, should depend on the clarity of the percept. The high risk of gambling should induce subjects to commit themselves only when they are relatively certain of their response.

This situation may be restated in terms of the perceptibility model proposed in the introduction to Experiment III. That is, if the subject reliably responds "I don't know", whenever the category of the item is uncertain, then the response selection matrix ([3]) becomes the identity matrix, such that the stimulus-response relationship is fully specified by matrix [2]. Thus, in this situation, the probability of gambling on a given class of stimuli should directly reflect its perceptibility. Once again, if there are no differences in the perceptibility of the stimuli, then the value of n_t should be greater than or equal to the value of w_t.

Method

Subjects. The subjects were eight adults with normal or corrected-to-normal vision. Each subject was given $0.50 at the beginning of a session and, in addition, was allowed to keep whatever she or he won during the course of the experiment.

Apparatus and Material. The stimuli and apparatus were the same as in Experiment III.

Procedure. Each subject received 440 categorization trials. There were 44 words, 22 pseudowords, and 22 nonwords at each of the SOA's of 5, 15, 25, 35, and 45 msec. The sequences of stimuli, stimulus categories and SOA's were separately randomized for each session. Since there were only 300 stimuli but 440 trials, almost half of the stimuli of each type were presented twice in a session; after the first 300 trials, the stimuli were reshuffled.

The subject was to respond "word", "not a word", or "I don't know" on every trial. If the subject responded "word" or "not a word" and was correct,

she or he was immediately given a penny; if the subject was incorrect, five pennies were taken away. When the subject responded "I don't know", she or he neither won nor lost any money. The first 40 trials were not scored; they were included to allow subjects' gambling behaviors to stabilize. If a subject lost any of the initial $0.50 during these 40 trials, she or he was reimbursed. The instructions, warm-up trials, and procedures were otherwise the same as in Experiment III.

Results and Discussion

Errors. The pay-off matrix proved to be quite effective in minimizing guessing; only 2.5% of the responses were incorrect. These errors were not evenly distributed across stimulus conditions ($F(2,14) = 6.37$, $p<.05$). Pseudowords were incorrectly categorized significantly more often than either words or nonwords, while the number of errors did not differ between the latter two conditions (Newman-Keuls, $p<.05$).

INSERT FIGURE 7

The percentage of errors at each SOA is shown in Figure 7 for each stimulus type. These error distributions bear a strong resemblance to those obtained in Experiment III. Specifically, the bias seems to shift from nonword toward word responses with increasing SOA. As in Experiment III, the subjects' explanation for this was that the words stood out more than the other stimuli so that if a stimulus seemed very clear, then they tended to believe it was a word even if they failed to recognize it; if it seemed fuzzy, they tended to believe it was a nonword.

Since the first two subjects insisted on knowing what the stimulus had been when they erred, this was made a matter of policy. This procedure

provided additional insight into the nature of the error responses. For example, the three stimuli wime, bome, and tive evoked 47.2% of the erroneous pseudoword categorizations. Subjects tended to perceive these stimuli as wine, home or bone, and five. This suggests that a large proportion of the errors to pseudowords were due to failures in fine discrimination.

Under the pressures of this experiment, the subjects' overt behaviors became very interesting. Often subjects would become adamant about what they had "seen". Sometimes their mistakes revealed impressive transformations of the stimuli. The most striking example is probably the subject who insisted that he had seen snow when the actual stimulus was uwos. A very common tendency of subjects was to count the letters of perceived words on their fingers to make sure that there were exactly four; if not, they responded "nonword". It is clear that they found it difficult to distinguish sensation from hallucination.

Perceptibility. The probabilities of gambling differed significantly across stimulus conditions ($F(2,14) = 4.12$, $p<.05$). Subjects were significantly more likely to accept the gamble for words than for pseudowords or nonwords whereas the probabilities of accepting the gamble did not differ between the latter two conditions (Newman-Keuls, $p<.05$). Moreover, the word advantage held for every individual subject. Since the probabilities of accepting a gamble are direct estimates of w_t, p_t, and n_t, these results indicate that words are, in fact, differentially perceptible. This conclusion is especially bolstered by the fact that w_t was significantly greater than n_t. The group functions for w_t, p_t, and n_t are provided in Figure 8.

INSERT FIGURE 8

Summary of Experiment IV

The subjects themselves may have provided the best summary of these results in claiming that the words "popped out" at them. Despite this experiment's having been designed to promote a nonword advantage, every subject demonstrated a word advantage. The nature of subjects' errors indicated that their percepts were shaped in part by top-down influences; their knowledge of words evidently worked to organize and supplement the information they extracted from the stimulus. Further, it may be inferred that the operation of these influences was entirely automatic, in view of the deliberate routines subjects developed to correct for them. Subjects' errors, introspections, and, perhaps most convincingly, even the strategy they reportedly used for gambling their money indicated that whatever the mechanisms underlying the top-down processes, they affected the very image of the stimulus.

GENERAL DISCUSSION

The major results of these experiments can be very briefly summarized. First, the word advantage is evidently mediated, in part, by perceptual as opposed to response processes. Second, in terms of basic information-processing parameters, the processing of words and nonwords appeared quite similar; the two major differences were that the component letters of words, in contrast with those of pseudowords and nonwords, were found to be processed nonindependently, and that the letters of words and pseudowords were reported in their correct positions more often than the letters of nonwords. Third, although identity and positional information are

evidently extracted by separate mechanisms, they exhibit a mutual dependence. On one hand, analyses of the subthreshold data from Experiments I and II suggested that the abrupt leap in letter identification accuracy corresponding to 0 msec SOA was potentiated by the extraction of a critical amount of order information. On the other hand, subjects' special difficulty with the order of the letters of nonwords suggests that positional information is quite weak at shorter exposure durations unless it is reinforced by orthographic constraints. The remainder of this discussion will be directed towards fitting these results against the theoretical alternatives considered in the introduction.

The first set of explanations for the word advantage held that the unit of perception differed between words and nonwords. More specifically, it was hypothesized that the perceptual units underlying word recognition correspond to whole words (e.g., Cattell, 1886a) or spelling patterns (e.g., Gibson, Pick, Osser, & Hammond, 1962) whereas the units underlying the perception of nonwords correspond to single letters. If either of these hypotheses were correct, then the word advantage should have been substantially reduced by the typographic manipulations introduced in Experiment II. However, the distortions in word-shape in Experiment II were no more damaging to the perception of words or pseudowords than they were to the perception of nonwords. These results not only refute the perceptual unit hypothesis, but, further, attest that the identification of words depends very slightly, if at all, on letter cluster or word shape cues. Rather, the fundamental units of perception for words, pseudowords, and nonwords alike, are apparently single letters.

Moreover, the results of Experiments I and II indicate that the processing of words, pseudowords, and nonwords is quite similar at the level of visual analysis. No differences were found in the temporal order of feature extraction: the component letters of all three types of stimuli were apparently encoded in parallel. Similarly, no differences were found in the spatial distribution of attention: it was generally biased from left to right. Finally, there was no evidence that people are differentially sensitive to the visual features of words, pseudowords, and nonwords.

The results of Experiments I and II are much more compatible with the sophisticated guessing models. According to these models, the parameters of the feature extraction process depend strictly on the visual clarity of the display. Thus, the processing of words, pseudowords, and nonwords is not expected to differ at the level of visual analysis. Further, since literal features are taken to be the units of perception, the typographic irregularities introduced in Experiment II are expected to exert a comparable effect on the perceptibility of words, pseudowords, and nonwords. Rumelhart and Siple's version of the model additionally predicts several other aspects of the data. First, it predicts the existence of a recognition threshold for quadrigrams. Second, it predicts that the probability of a subject's correctly completing a stimulus should be greater for high frequency words than for pseudowords, and greater for pseudowords than for nonwords. Further, since the clarity of the percept is supposed to increase with effective exposure duration, the contribution of guessing is supposed to decrease; thus, the model also predicts that the stimulus effect should be most marked at shorter suprathreshold SOA's. Finally, since the decision process purportedly operates at the level of word selection for word responses, but at

the level of letter selection for pseudoword and nonword responses, the model predicts the differential nonindependence among the component letters of words.

In general, then, sophisticated guessing models can account for the data from Experiments I and II quite well. But, as was argued in the introduction, something like sophisticated guessing must be a normal aspect of word recognition. The issue surrounding such models is, then, whether they can provide a complete explanation of the word recognition process. With respect to the results of Experiments I and II, the only serious shortcoming of Rumelhart and Siple's model has to do with the perceptibility of positional information. Since the response selection rules of their model depend heavily on the string position of the perceived features, it is reasonable that the quadrigram recognition threshold should depend on the criterial extraction of positional information. However, it is not clear how, without sacrificing considerable power, the model could be accommodated to the evidence that positional information is not reliably perceived at suprathreshold exposure durations. In any case, the results of Experiment IV challenge the adequacy of any sophisticated guessing theory.

With respect to sophisticated guessing models, the design of Experiment IV was not only intended to eliminate the hypothetical source of the word advantage but, further, to set up a nonword advantage. That is, of words, pseudowords, and nonwords, only nonwords can be definitely categorized on the basis of partial information. Whereas distinctions between words and pseudowords depend on the encoding of all of their letters, the categorization of nonwords requires the identities of as few as two of their letters. Thus, if the stimuli were equally perceptible, as sophisticated guessing models

assert, then for effective exposure durations between threshold and asymptote, nonwords should have been correctly categorized most often. By contrast, words were categorized most often by every subject, which can only mean that they were differentially perceptible.

Of the theoretical explanations for the word advantage that were considered in the introduction, only the criterion bias model remains. The essence of the criterion bias model is that high frequency words should be more perceptible than other graphemic strings despite the fact that people are no more sensitive to their visual properties. To this extent, the criterion bias model is uniquely compatible with the results of the present experiments. However, no specific version of the criterion bias model can wholly account for the data.

Both Broadbent (1967) and Morton (1969) attribute the word advantage to the existence of word detection units. According to both of these theories, the amount of sensory information that is required to trigger these units depends directly on their past frequency of occurrence. Thus, high frequency words may be perceived on the basis of relatively little sensory information. Further, since the sensory information is mapped against whole-word codes, the obtained nonindependence among the component letters of words would be expected. Yet, these two authors are equally vague as to the mechanisms that mediate the word facilitation: whereas Broadbent suggests that the criterion is lower for high frequency words, Morton suggests that the threshold is lower for high frequency words. Moreover, neither theory can account for the differences in report accuracy between pseudowords and nonwords, or the data on positional information, or the fact that the fundamental units of perception seem to be single letters anyhow.

Smith's (1971) version of the criterion bias model is equally unsatisfactory, if only because it is more explicit. He, too, attributes the word advantage to the operation of whole-word units. However, unlike Broadbent (1967) and Morton (1969), Smith specifies that these units are composed of ordered arrays of letter recognition units. In this way, Smith's theory is additionally compatible with both the evidence that letters are the fundamental units of perception and with the evidence that the recognition threshold for quadrigrams depends on the extraction of a critical amount of order information.

Yet, Smith's theory is, at its core, a word-shape theory. He assumes that both individual letters and words can be analyzed into finite sets of physical features, and that perception essentially consists in pattern matching routines on these features. The word advantage arises because an acceptable match may be obtained at the word level before a sufficient number of features has been encoded to determine unambiguous matches for all of its component letters had they been presented in an unfamiliar arrangement. Smith recognizes the dependence of this theory on word shape and tries to accommodate normal variations in typestyle by proposing functionally equivalent recognition units for distinctly different allographs, like **A** and **a**. Smith concludes that variations in typeface should not interfere with word perception, unless they carry concomitant disruptions in word-shape (Smith, Lott, & Cronnell, 1969). Thus, in the context of Experiment II of the present study, Smith's theory also becomes inadequate. The fonts in Experiment II were chosen to be as diverse as possible, specifically so that both word-shape cues and between-letter feature predictability would be maximally disrupted. Even so, the magnitude of the word advantage did not diminish.

What is needed, then, is some version of the criterion bias model that is capable of explaining the perceptual phenomena supported by the present experiments. The theory must be able to explain the differences in the identifiability of words, pseudowords, and nonwords, but still maintain that letters are the units of perceptual analysis. The theory must incorporate the passive facilitation of word perception without invoking explanations related to differential sensitivity or supraliteral visual cues. In addition, the theory should be able to encompass the positional effects borne out by the present studies.

In keeping with the data, let us suppose that the extraction of visual information proceeds in the same way for all types of graphemic strings. More specifically, the visual information is extracted from individual letters in parallel (Estes, 1975; Travers, 1975; Sperling, 1967), but with a left-to-right bias in attention. This process may be conceptualized according to Rumelhart's (1970) theory of the visual encoding of graphemic arrays, except that it seems inappropriate to quantize the visual information into discrete features. Suppose, instead, that the information extracted from each letter is mapped onto internal distributions, which, by their central tendencies, define prototypical letters (Posner, 1969). In this way, the recognition of letters could proceed without any stringent constraints on their physical configurations. It must also be the case that the strength of the association between the identity of a letter and its position in the string only gradually increases with effective exposure duration.

Notably, once all of the letters of a string have been fully identified, all opportunities for perceptual enhancement are gone. Therefore, if the visual information extracted from words, pseudowords, and nonwords is

similarly mapped onto single letter units, then any perceptual advantage of words must be due to a differential accessibility of the single letter units.

The explanation that I would like to suggest for the perceptual advantage of words is based on an old idea: namely, that any two internal units that are repeatedly activated at the same time, will come to be associated such that activity in one facilitates activity in the other. Specifically, I would like to suggest that such associations exist between letter recognition units. This hypothesis is illustrated in Figure 9. The circles in Figure 9 represent letter recognition units, the arrows represent associations between them. The full circles correspond to units receiving activation both directly from the stimulus and indirectly through other units while the broken circles correspond to units receiving indirect activation only. The degree of interfacilitation between units should be determined by both the strength of the external input and the strength of their association. Since the latter is presumably a function of the letters' history of co-occurrence, it can be estimated from transitional probabilities; the values given beside the arrows in Figure 9 were taken from Mayzner and Tresselt's (1965) norm. The direction of the arrows does not constrain the flow of activity but merely indicates the direction of the transition. For example, in Figure 9A when the A unit receives input, the facilitation of the T unit is weighted by 0.030 for T's to the immediate left of the A in the input string, and by 0.111 for T's to the immediate right of the A in the input string.

INSERT FIGURE 9

This schema would predict a considerable perceptual advantage of words and pseudowords over nonwords, especially given that the extraction of visual information proceeds in parallel. That is, interfacilitation between the

component letters of words and pseudowords would be mutual and coincident with external input. With reference to the example in Figure 9A, the T, the H, and the A would all be simultaneously receiving direct activation from the stimulus and indirect activation from each other. By contrast, the activation of the component letters of nonword strings, as in Figure 9C, would depend almost entirely on external input; since the transition probabilities between the adjacent letters of nonwords are quite small, their mutual facilitation must also be minimal.

A further advantage of this schema is that it can explain the differences in positional accuracy between words, pseudowords, and nonwords. That is, for words and pseudowords, positional information is largely redundant with the interletter associations. Because of this, for words and pseudowords, missing positional information will be passively constructed, and weak positional information will be reinforced. By contrast, given the way the nonwords were generated, the strongest associations between their component letters would most probably conflict with the actual positional information. For nonwords, then, missing positional information will be incorrectly constructed, and weak positional information may suffer interference. The implication with respect to Experiments I and II is that the accuracy with which positional information was reported was probably better for words and pseudowords, but worse for nonwords than it would have been on the basis of its perceptibility alone.

Even so, the schema does not provide an adequate foundation for the results of the present experiments. In particular, it predicts no advantage of words over well-formed pseudowords. In order to capture the reader's knowledge of words, a second, lexical level of analysis must be included in the model. This level is represented in Figure 10. The connections between

the lexical units and the letter units correspond to the associations between these units. The weighting of these associations are supposed to depend on lognormal word frequency and the coefficients are taken from Carroll, Davies, and Richman (1971) Standard Frequency Indices. Like the interletter associations, the associations between the word and the letter units are supposed to be bidirectional: as the individual letter units receive input, they will relay activation to all appropriate word units, and as they activate a given word unit, it will proportionately and reciprocally facilitate the letter units corresponding to its component letters. It is significant that the word units are not activated directly by the stimulus, but only indirectly, through the letter units. Because of this, the system, while being affected by the discriminability of individual letters, will be oblivious to the shapes of whole words. In addition, if word recognition is mediated by weakly ordered, individual letter units, then the involuntary permutations of nonwords into words that were observed in Experiment IV are to be expected; in contrast, they would be very difficult to explain if words were recognized directly and holistically.

INSERT FIGURE 10

The facilitory effect of the lexical units should result in the perceptual enhancement of words as compared to pseudowords. Moreover, the magnitude of the word advantage should be a function of word frequency. The existence of such lexical units would also explain the perceptual nonindependence that was found among the component letters of words. That is, if activation is criterially, even if not uniquely, distributed across the units corresponding to the component letters of a high frequency word, the corresponding word unit should be evoked, resulting in the recognition of the

whole word. Notably, such an associated lexical network could also provide a perceptual basis for the letter hallucinations described by Pillsbury (1897) and reported in the present study.

Throughout this paper, we have been comparing and contrasting data which were obtained through a variety of procedures. The guiding assumption has been that although people can adjust their performance strategies in response to situational demands, they cannot alter the perceptual mechanisms and knowledge base on which those strategies operate. Indeed, a basic tactic of this study was one of deliberately manipulating subjects' strategies so as to vary the perspectives from which we peered into their underlying resources.

The proposed model, however, points out a way in which the procedures used in all of these experiments interfered with the perceptual processes themselves. Under normal reading conditions, stimulation from the interunit associations may facilitate perception of the sensory information, but should not supplant or override it. Although the higher order goal of the network is that of recognizing words, its activity centers on confirmation of the letter units. The letter units are the foci of direct activation from the stimulus as well as indirect activation from both word units and other letter units in the network. The associations have their effect by relaying a proportion of the activation a unit is receiving to other units with which it frequently co-occurs. Where such indirect activation coincides with direct activation, it may effectively speed stimulus processing; however, where it is at variance with direct activation, it cannot ultimately compete. In contrast, the masking procedure used in these experiments, must have unnaturally and often prematurely aborted the direct activation from the stimulus. The effect of early imposition of the mask would be to disperse direct activation across the

letter network such that the most pronounced pattern of activity would be that which was sustained by the top-down mechanisms that had already been triggered by the stimulus. In addition, the influence of these mechanisms was surely exaggerated by the procedure of requiring subjects to respond even when they insisted that they had seen nothing but the mask. (As an aside, a surprising number of such responses were correct.) While it is important to recognize these distortions when extrapolating from these data to the normal reading situation, it should also be recognized that it was largely because of these distortions that we were able to witness the nature and automaticity of the reader's top-down processes.

The proposed version of the criterion bias model is not very different in effect from sophisticated guessing models. The word advantage arises because of the subject's tendency to fill in the blanks in accordance with her or his linguistic experience. The critical difference is that under the criterion bias model, the process of stimulus impletion is passive -- it is implicit in the structure of the memory. The same model could be used to account for sophisticated guessing inasmuch as sophisticated guessing theories presume that the same sort of information exists in memory. It seems reasonable that criterion bias models and sophisticated guessing models are actually two of a kind, but represent different points on a continuum; that is, the only difference between them may be in how much extra-stimulus information the subject needs to apply actively in order to arrive at a response. The structure of this model is also appealing in that it almost begs to be extended upwards to a lexical meaning level, a syntactic level, and so on (see Adams & Collins, in press). In any case, the model seems to do a good job of explaining the impressive facility with which people recognize words, and does so in a way that relieves the homunculus from most of the burden.

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Footnotes

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Table 1

The percentage of correctly categorized words, pseudowords, and nonwords as a function of stimulus onset asynchrony for each subject in Experiment III.

		Stimulus Onset Asynchrony				
		5	15	25	35	45
S1	Word	36.7	56.7	88.3	98.3	100.0
	Pseudoword	70.0	63.3	50.0	73.3	60.0
	Nonword	56.7	36.7	36.7	63.3	86.7
S2	Word	3.3	78.3	96.7	100.0	100.0
	Pseudoword	83.3	83.3	66.7	90.0	86.7
	Nonword	96.7	83.3	93.3	86.7	96.7
S3	Word	40.0	53.3	65.0	90.0	96.7
	Pseudoword	63.3	66.7	53.3	56.7	63.3
	Nonword	53.3	56.7	36.7	60.0	80.0
S4	Word	53.3	56.7	98.3	100.0	100.0
	Pseudoword	16.7	53.3	66.7	63.3	90.0
	Nonword	30.0	70.0	76.7	90.0	96.7
S5	Word	20.0	38.3	70.0	95.0	100.0
	Pseudoword	83.3	63.3	36.7	13.3	43.3
	Nonword	96.7	70.0	73.3	63.3	63.3
S6	Word	48.3	68.3	100.0	100.0	100.0
	Pseudoword	56.7	43.3	76.7	86.7	100.0
	Nonword	43.3	63.3	93.3	96.7	100.0
S7	Word	18.3	80.0	91.7	100.0	100.0
	Pseudoword	86.7	53.3	23.3	40.0	56.6
	Nonword	93.3	33.3	63.3	53.3	70.0
S8	Word	55.0	51.6	85.0	98.3	100.0
	Pseudoword	63.3	66.7	50.0	66.7	83.3
	Nonword	50.0	63.3	70.0	70.0	73.3
$\bar{S}$	Word	34.4	60.4	86.9	97.7	99.6
	Pseudoword	65.4	61.7	52.9	61.3	72.9
	Nonword	65.0	59.6	66.7	72.9	83.3
	Total	49.8	60.5	73.4	82.4	88.9

Table 2

Estimated values of the parameters, g, σ_t, $v_{p,t}$, and $v_{n,t}$, from Matrix [7] as a function of stimulus onset asynchrony for each subject in Experiment III.

		Stimulus Onset Asynchrony				
		5	15	25	35	45
S1	g = 0.367					
	σ_t	0	0.316	0.736	0.974	1.000
	$v_{p,t}$	0	0.633	0.321	0.735	0.600
	$v_{n,t}$	0	---	0.271	0.633	0.867
S2	g = 0.067					
	σ_t	0	0.767	0.965	1.000	1.000
	$v_{p,t}$	0	0.803	0.657	0.900	0.867
	$v_{n,t}$	0	0.803	0.829	0.867	0.967
S3	g = 0.408					
	σ_t	0	0.211	0.409	0.831	0.944
	$v_{p,t}$	0	0.948	0.447	0.561	0.636
	$v_{n,t}$	0	0.474	0.041	0.602	0.812
S4	g = 0.650					
	σ_t	0	---	0.951	1.000	1.000
	$v_{p,t}$	0	---	0.683	0.633	0.900
	$v_{n,t}$	0	---	0.788	0.900	0.967
S5	g = 0.150					
	σ_t	0	0.274	0.647	0.941	1.000
	$v_{p,t}$	0	0.060	0.104	0.088	0.433
	$v_{n,t}$	0	0.303	0.669	0.620	0.633
S6	g = 0.492					
	σ_t	0	0.397	1.000	1.000	1.000
	$v_{p,t}$	0	0.309	0.767	0.867	1.000
	$v_{n,t}$	0	0.862	0.933	0.967	1.000
S7	g = 0.142					
	σ_t	0	0.767	0.903	1.000	1.000
	$v_{p,t}$	0	0.434	0.167	0.400	0.567
	$v_{n,t}$	0	0.173	0.609	0.533	0.700
S8	g = 0.492					
	σ_t	0	0.047	0.705	0.967	1.000
	$v_{p,t}$	0	---	0.497	0.672	0.833
	$v_{n,t}$	0	---	0.779	0.707	0.733

Figure Captions

Figure 1. Examples of word, pseudoword, and nonword stimuli from Experiment I.

Figure 2. Percentage of correctly reported letters for words (———), pseudowords (— — —), and nonwords (— - —) as a function of relative stimulus onset asynchrony for Experiment I.

Figure 3. P_t(Quadrigram) (———) and $P_t(\text{Letter})^4$ (- - - -) for words (○), pseudowords (□), and nonwords (△) in Experiment I.

Figure 4. Percentage of letters reported in the correct position for words (———), pseudowords (— — —), and nonwords (— - —) as a function of relative stimulus onset asynchrony in Experiment I.

Figure 5. Examples of the word, pseudoword, and nonword stimuli from Experiment II.

Figure 6. Percentage of correctly reported letters for words (———), pseudowords (— — —), and nonwords (— - —) as a function of relative stimulus onset asynchrony in Experiment II.

Figure 7. The percentage of erroneous categorization responses as a function of stimulus onset asynchrony for words, pseudowords, and nonwords in Experiment IV.

Figure 8. Group perceptibility functions for words (○), pseudowords (□), and nonwords (△), for Experiment IV.

Figure 9. Schematic of the associated letter network.

Figure 10. Schematic of the associated lexical network.

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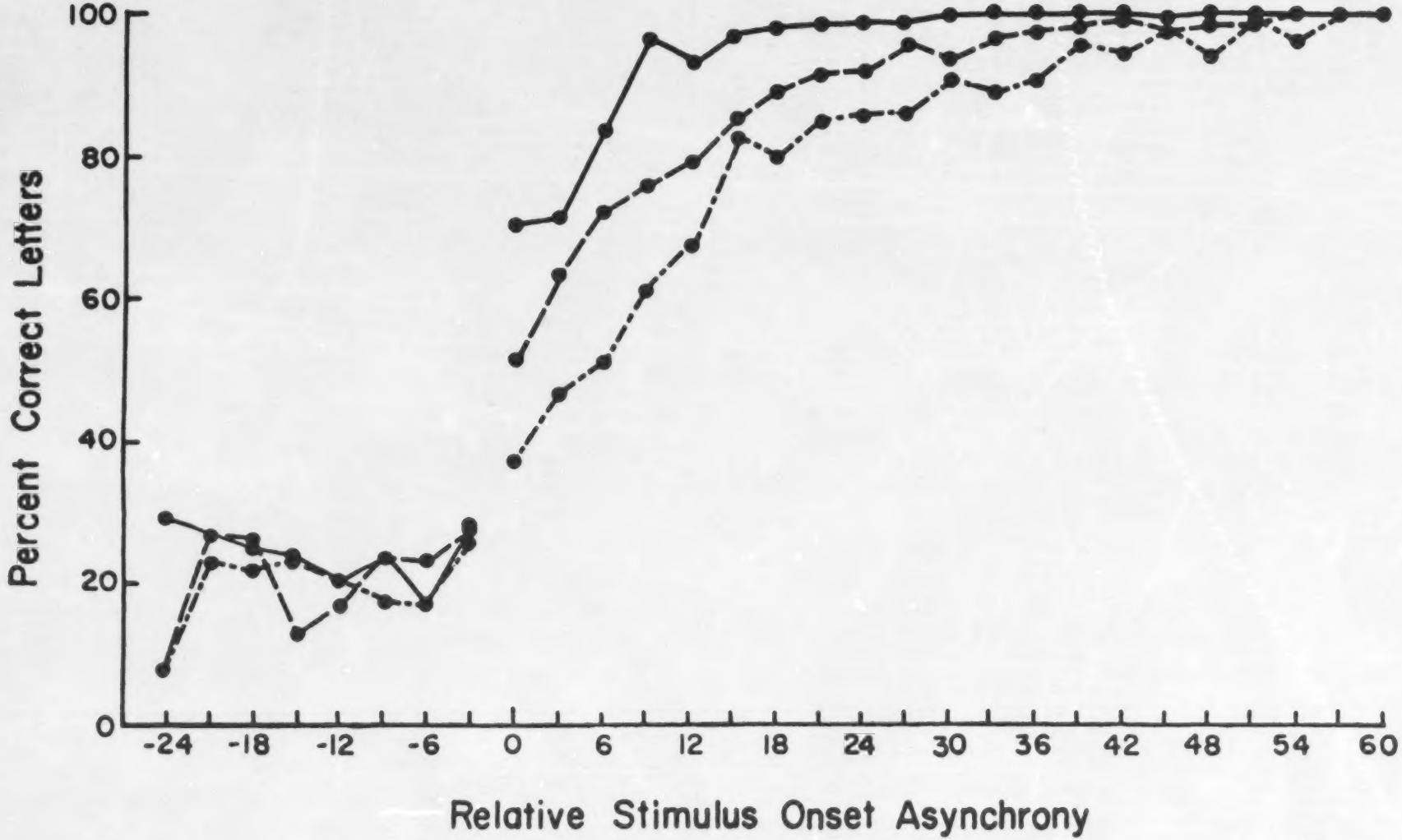
yibv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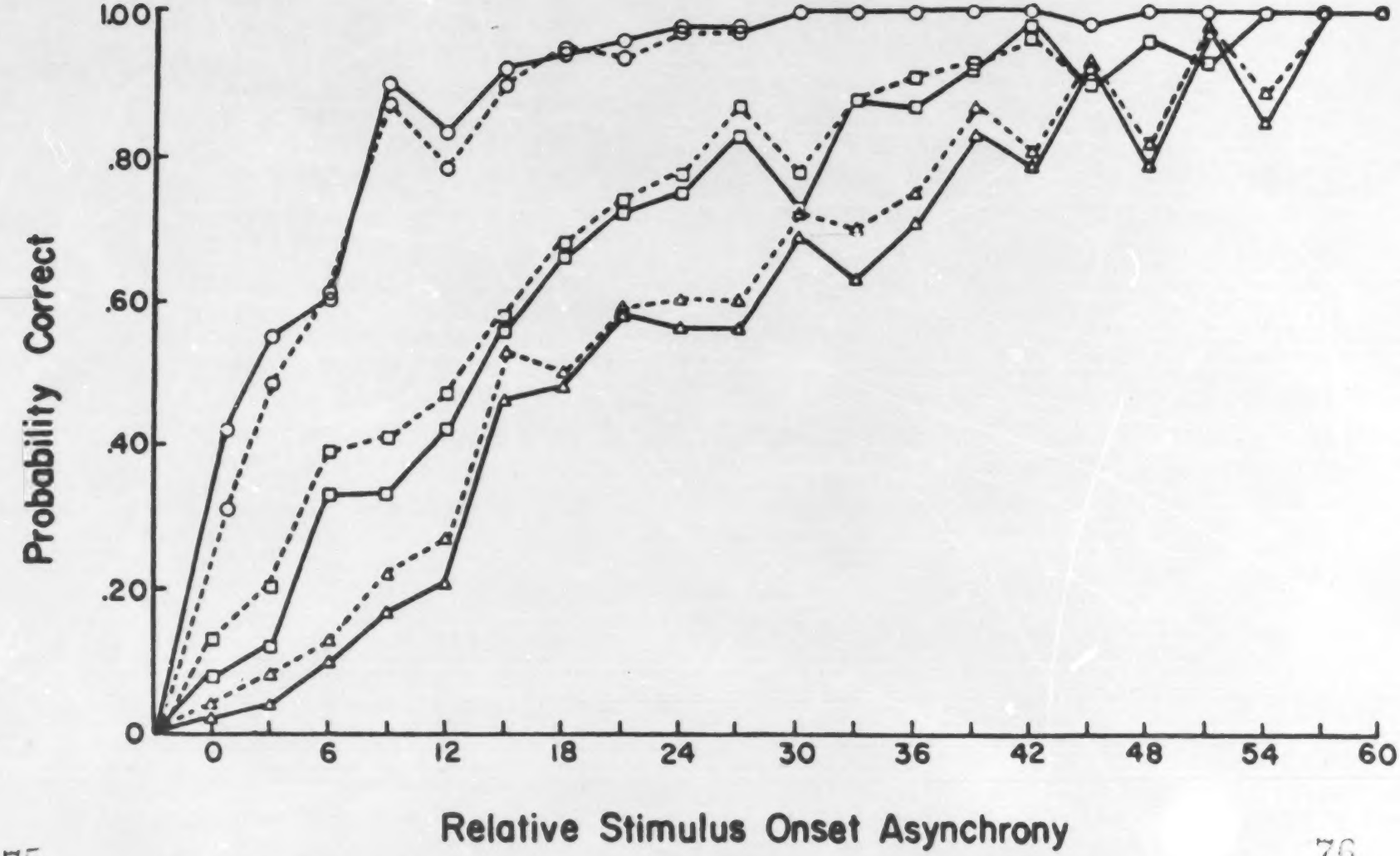
Relative Stimulus Onset Asynchrony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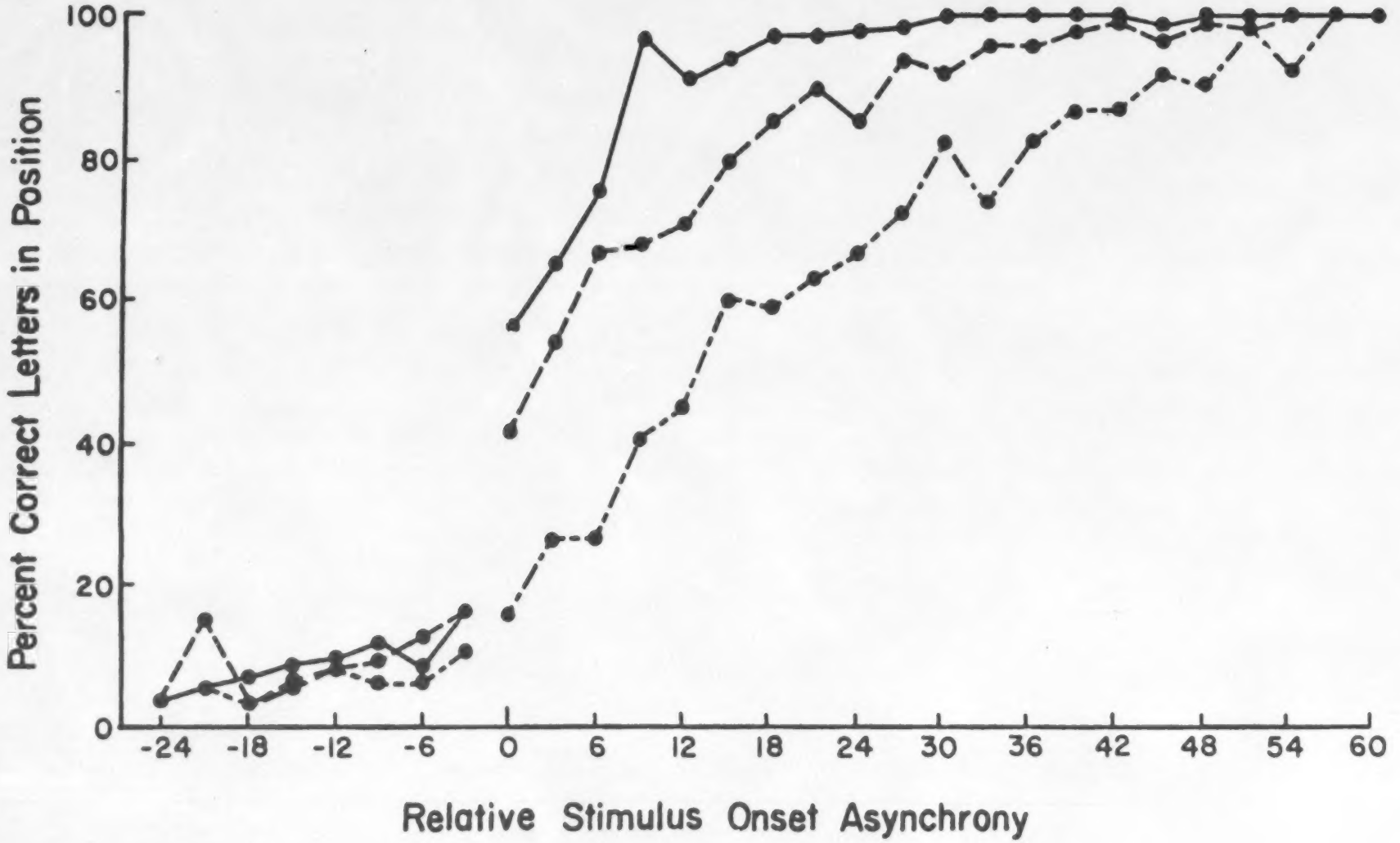
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Relative Stimulus Onset Asynchrony

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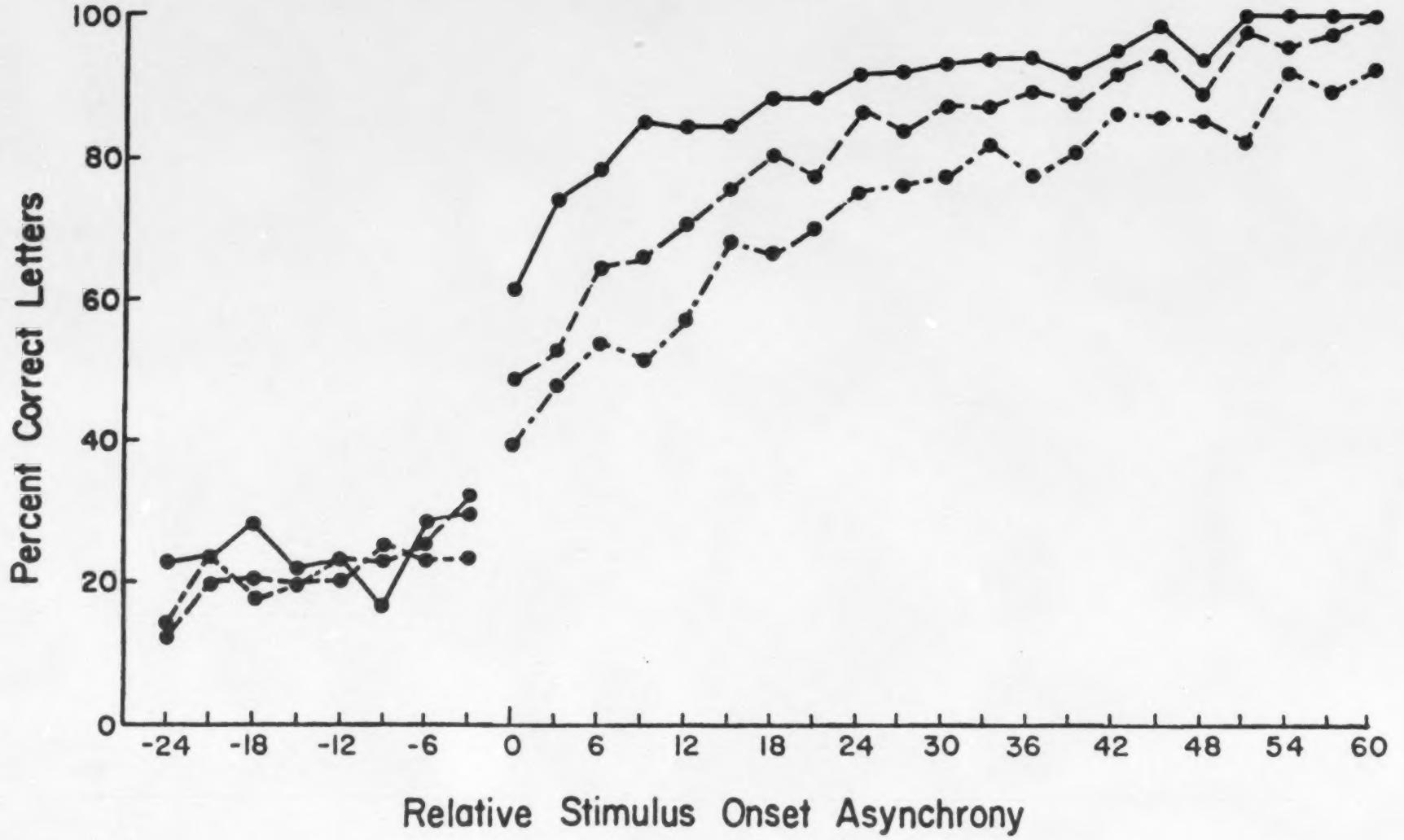
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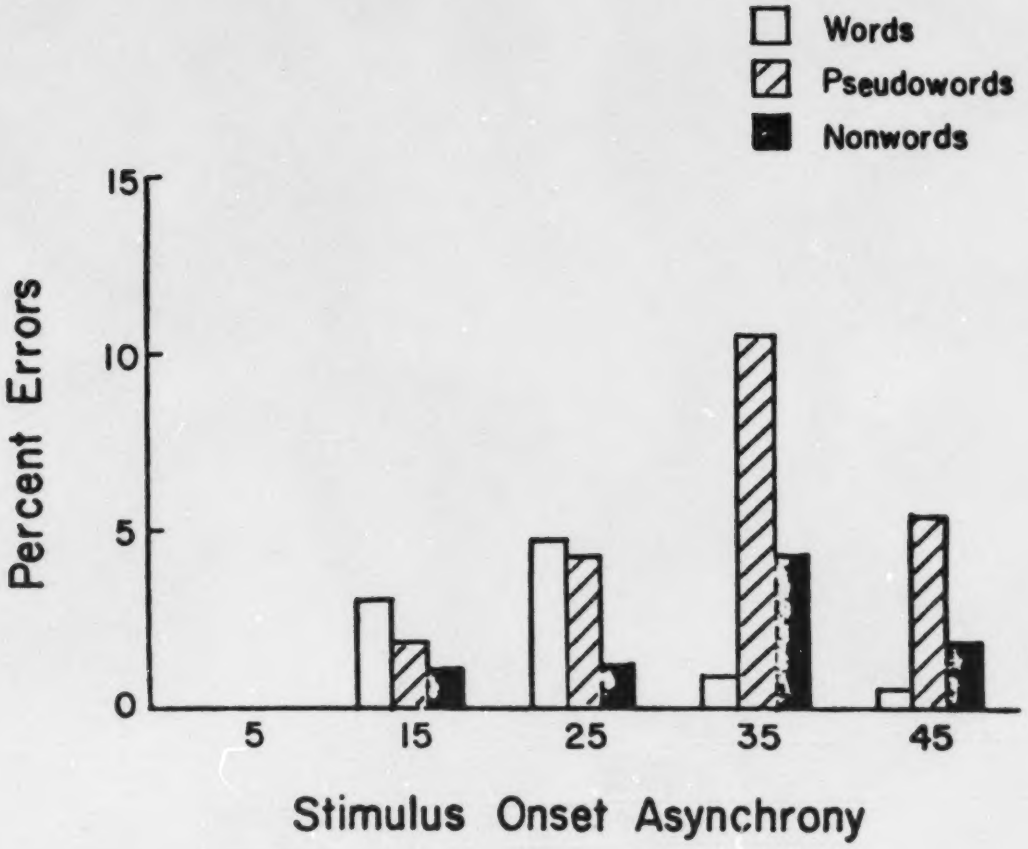
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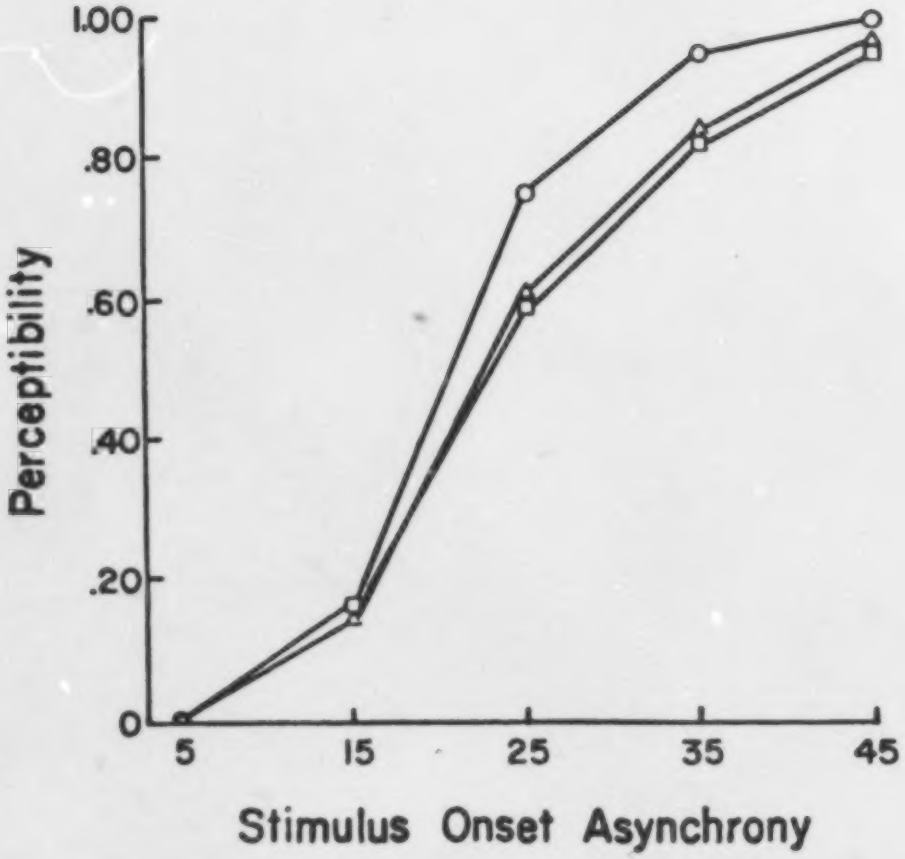
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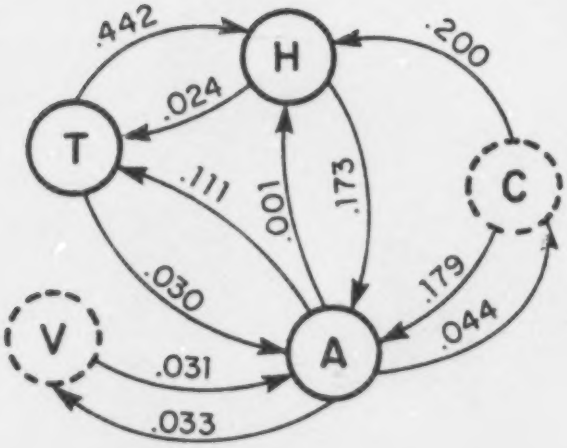

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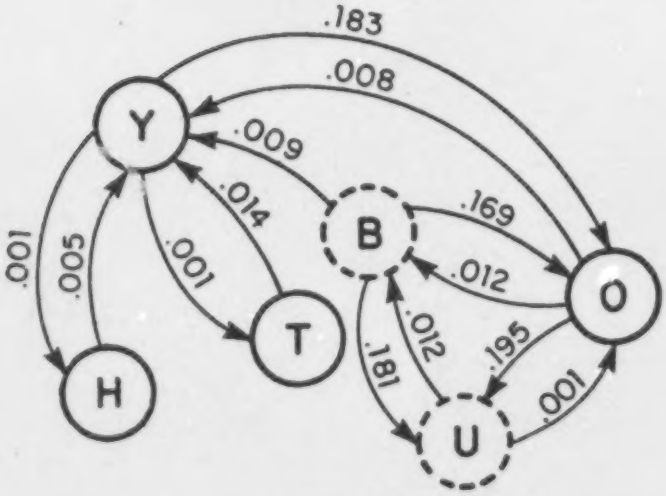

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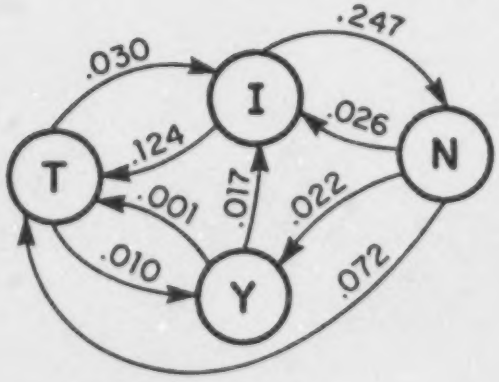

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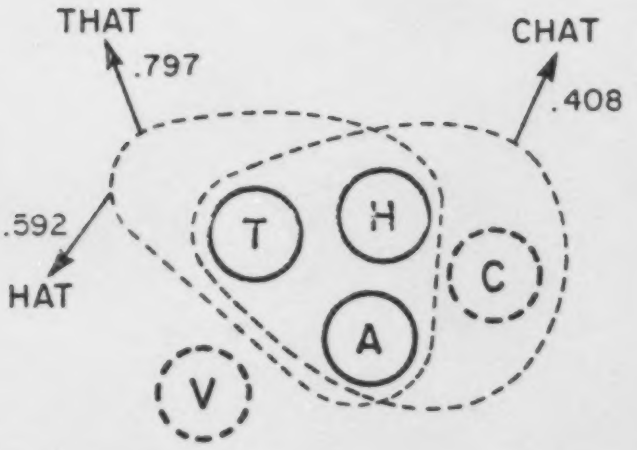

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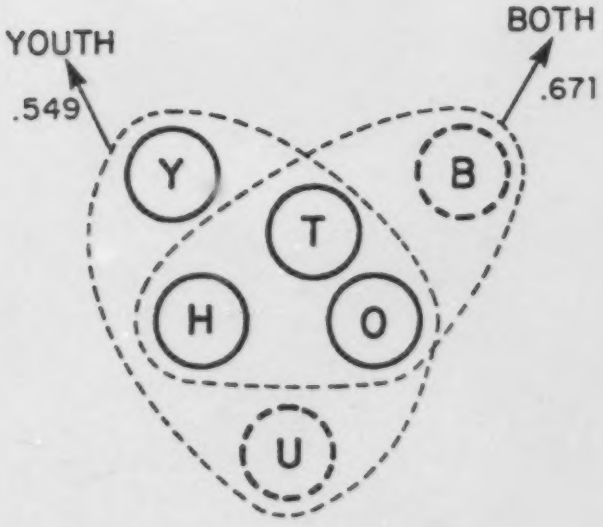

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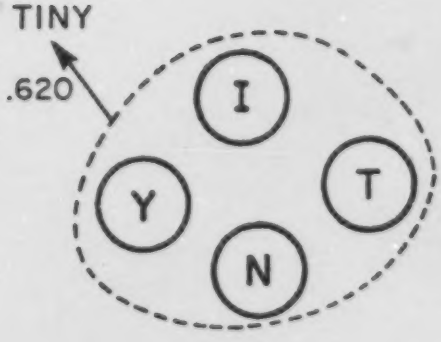

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